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14. ABSTRACT
The basic premise is that a legacy part design that was originally optimized for one manufacturing process may either be impossible to produce by another process, or too costly. To re-manufacture a replacement part, the original geometry and the material need to be modified; such modification must be done without violating the inter-facing, functional and structural constraints.
The Rapid Re-Engineering System (RRES) is envisioned to serve as a bridge between Geometry Extraction

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Legacy systems, re-engineering, material substitution, TechSpecs

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LSE Re-Engineering Testbed: Final Report

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Outline

- LSE Background
  - **Motivation & Broader Impacts for US Army**
  - **What is Legacy Systems Engineering**
- ASU Project Overview
  - **Major objectives**
  - **Status at a glance**
  - **Collaborations**
  - **Tech Transfer issues**
- Technical Details
  - **TechSpec formulation**
  - **Cost & Manufacturability evaluation**
  - **Material substitution**
  - **Assemby feature & load paths extraction (structural function)**

LSE BACKGROUND

Problem Significance to ARO

- The US military owns and operates many complex electro-mechanical systems, some that were designed 25-50 years ago.
- Continued maintenance requires spare parts but the original manufacturers may no longer be around to provide them.
- In some cases there might not be sufficient technical data available to the Army to allow replacement manufacturing; in other cases, replacement costs may be too high or have large delivery times
- to sustain such legacy systems in a cost effective manner and respond rapidly to demand, a holistic plan is needed
- Past research has produced many clever solutions to specific problems, particularly geometry extraction from legacy parts and automated CAD model re-construction from point clouds or paper drawings and reproduction of copies of the original part.
- The holistic plan must include a high degree of automation (to reduce manpower cost, expertise needed) and high degree of integration between the sub-systems
- to move from academic labs to the real world, such as Army facilities like Mobile Parts Hospitals (MPH), a major shift of strategy is needed

Design Automation Laboratory

Background: Terminology

REVERSE ENGINEERING

Producing as close of a replica of the original part as possible. Part specification may come from drawings or physical parts (used or pristine)

RE-ENGINEERING

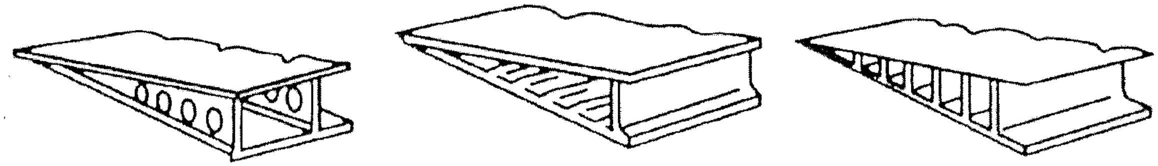
Selectively change some attributes of the original design, such as materials and geometry not constrained by interfacing requirements, etc. May be necessitated by inability to extract all engineering specs, unavailability of certain manufacturing resources, time/cost constraints, or desire to improve the design

RE-DESIGN

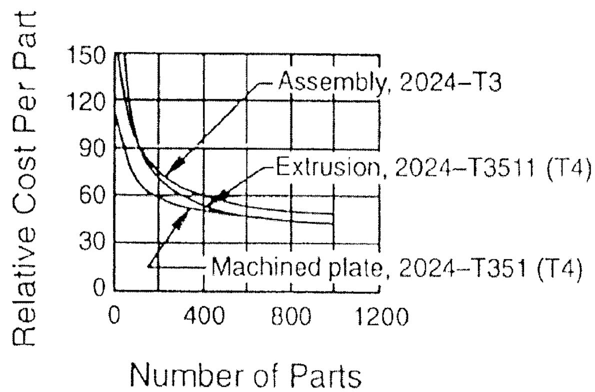
Replace the original part with an equivalent device, if it happens to be a standard device (motor, bearing, gear or gearbox, clutch, brake,etc.) or design a new component based only on the performance requirements and inter-facing constraints.

We refer to all of these collectively as "Legacy Systems Engineering"

Background: Manufacturing feasibility & economics



(a) Fabricated assembly (welded or riveted) (b) Extruded – single piece (c) Machined – from solid block



(d) Relative production costs vs production volume

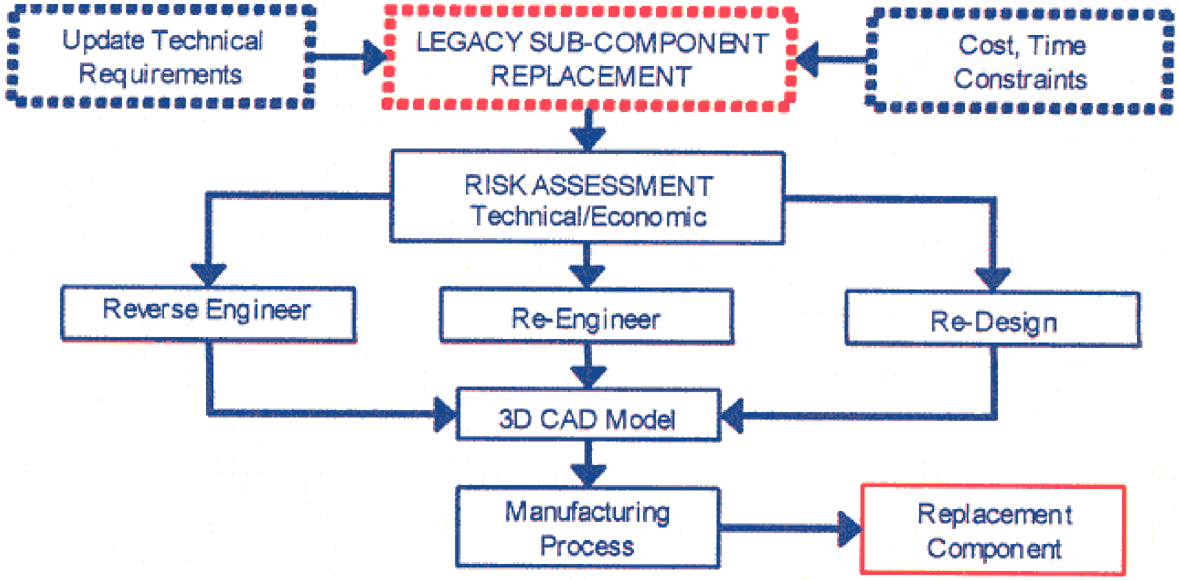
- ***A legacy part that was originally optimized for one manufacturing process may either be impossible to produce by another process, or too costly.***
- ***To re-manufacture a replacement part, the original geometry and the material may need to be modified;***
- ***such modification must be done without violating the inter-facing (geometric), functional and structural constraints*.**

Fig. source: Boeing Design Manual

Background: Viability of LSE

- **Must consider both technical and economic viability**
- **Tech Viability requires producibility evaluation that must be based on the manufacturing resources available**
- **Economic viability must take into account batch size and lead time. Special tooling, dies, molds, fixtures should be avoided, because small batch manufacturing cannot sustain the cost and the also because the lead times are large**
- **LSE must be heavily automated to minimize the cost in small batch production**
- **The consequences of design changes must be investigated with simulation tools and constraint based design systems; including functional and structural integrity.**

Which LSE Strategy is best?



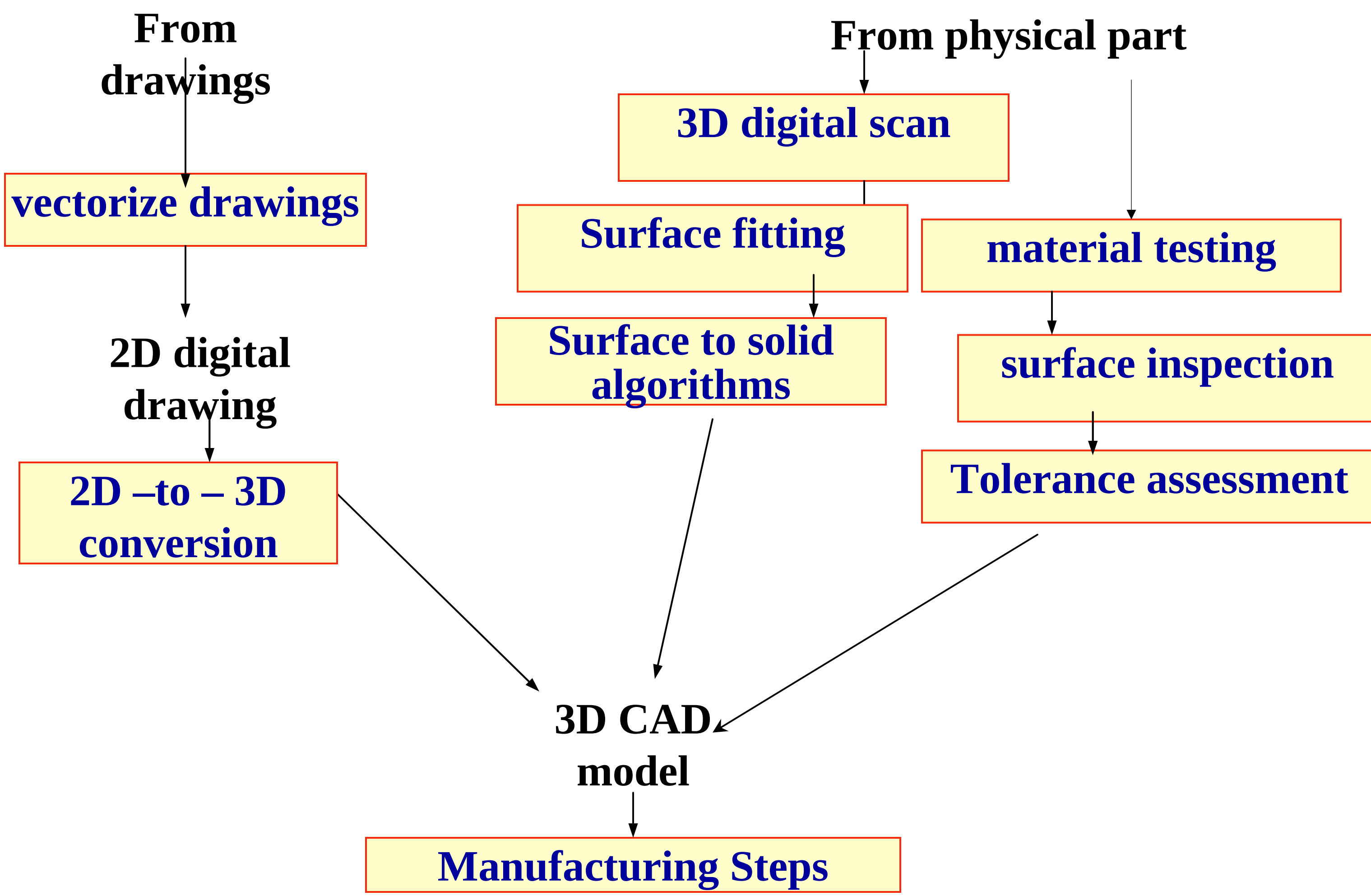
The decision depends on several technical and economic factors

How much information is known about the part?

- What form is the data in? (paper, digital, physical part …)
- How much will it cost to collect additional info needed?
- Is it a standard or non-standard part?

- What quantities are needed? how quickly? future demand?
  - What is the level of obsolescence of the embedded technology?
  - What is the complexity of the part? Degree of coupling with other subsystems?
  - Do we need and equivalent part or an improved/upgraded one?

Reverse Engineering Technologies



Re-engineering Tasks

From drawings or physical parts (see prev. slide) → 3D CAD model → Extract function & fit specs

↓

Manufacturability & Cost analysis

↓

Engineering analysis

↓

Material substitution

↓

Geometry modification

↓

Stress & failure analysis → manufacturing steps

ASU PROJECT: OVERVIEW

ASU Projects Particulars

- **Grant W911NF-05-1-0186**

  - Holistic Legacy Systems Engineering: Rapid Re-engineering System

  - Partial funding, $125k

  - Start date: 4/15/2005

Addendum 1

  - Material substitution pilot study

  - Funding $18.7k

  - Start date: 2/23/2006

Addendum 2

  - Semi automatic extraction of structural function

  - Funding, $13k

  - Start date: 2/22/2007

Project end date: 2/14/2009

ASU Projects Particulars

- **Develop technologies and tools to analyze and Redesign legacy parts that**
- **Must**
  - cost less
  - take least possible time to re-engineer and manufacture
  - be manufacturable with capabilities available in the field, such as Army MPH
- **Must not violate**
  - interfacing constraints
  - kinematic constraints
- **Must take the loads applied**

Cost of Legacy Systems Engineering

- Costs include:
  - forensic analysis
  - product teardown
  - measurements and test
  - analysis for re-engineering / redesign
- Because of small batch sizes and time (urgency), automation of these tasks is even more critical
- Which tasks can be automated and how?

LSE Holistic View

Stage 1

DATA EXTRACTION

- Extract geometry/features
- Find material properties
- Create CAD model

Stage 2

RAPID RE-ENGINEERING

- Extract Structural , functional requirements
- Redesign for economical production; generate alternatives
- Design eval: DfM & Cost analysis
- Structural analysis, simulation
- Constraint evaluation

Stage 3

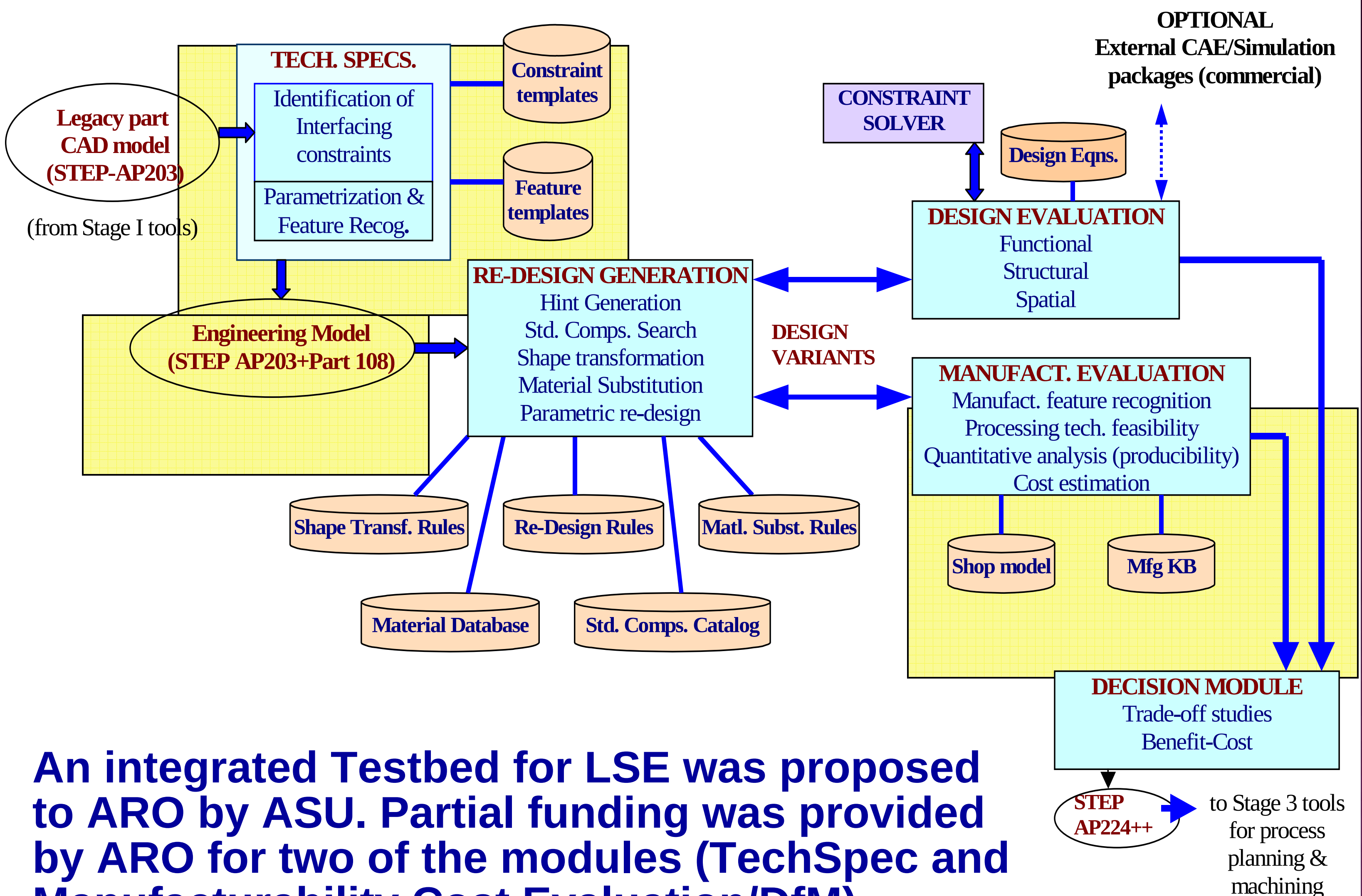
RAPID RE-MANUFACTURING

- Automated manufacturing planning
- On-site, small batch machining & fabrication

- **Prior research in Reverse Engineering has produced**
  - **(i) Methods for extracting geometric information from legacy parts/drawings;**
  - **(ii) produce near exact replicas of original parts;**
  - **(iii) Techniques to automate manufacturing planning tasks.**
- **Observation: the above tasks are necessary but not sufficient; the technologies in Stage 2 are missing**

Our goal is to explore a holistic strategy to make LSE technologies economically viable and technically practical for field deployment.

Integrated LSE System Proposal



An integrated Testbed for LSE was proposed to ARO by ASU. Partial funding was provided by ARO for two of the modules (TechSpec and Manufacturability Cost Evaluation/DfM)

Subsequent partial funding for pilot studies of material substitution and function extraction

Project Status at a glance

- Rapid Re-engineering System (RRES)
  - TechSpec Data model: completed
  - TechSpec module: partial implementation done
  - DfM Testbed: completed and adapted to RRES
  - Interfacing TechSpec with DfM: planned
- Material substitution pilot study
  - Database design: done
  - Substitution rules: initial set
  - Material DB population (pilot): proof of concept
- Semi automatic extraction of structural function
  - Theoretical formulation: done
  - Mating feature extraction algorithms: in progress
  - Software implementation: future

Synergistic collaborations

- ASU is also part of a multi-university consortium called VPERC (Virtual Parts Engineering Research Consortium)
- VPERC includes U. Utah, Hampton University and several small businesses (manufacturing shops)
- VPERC also has association with Focus Hope, TARDEC and TACOM
- Each university partner is funded separately by ARO
- U. Utah researchers specialize in digital scanning and surface reconstruction; Hampton has expertise in non-destructive testing techniques for materials, as well as, some imaging methods for assemblies before taking them apart
- ASU expertise is in engineering design, manufacturability evaluation and precision engineering

Project Needs & Tech Transfer

- **Technical Data Packages**
  - from our TARDEC contact (T. Wagner) and TARDEC contacts (G. Moeller, T. Richman) we have managed to get only two sets of specs for real legacy parts and assemblies – candidates for LSE
  - the project needed more example TDPs of mechanical assemblies or parts, particularly load bearing parts or castings, but this did not happen
- **Tech Transfer**
  - we would like to arrange face to face meetings with maintenance shop personnel to solicit their opinion on usability and customizability of the DfM Testbed
- **Additional RRES modules**
  - so far ARO has funded only TechSpec and DfM modules; Design Generation and Design Evaluation Modules were left open for future funding

ASU PROJECT:
Technical Details

Technical Tasks

- determine technical specification content required for re-engineering (form, fit, function)

- design neutral data model for Tech Specs including kinematic, assembly and spatial constraints

- design constraint management system

- develop a method for extracting kinematic and structural function based on screw theory

- design and implement a customizable DfM and Cost shell, populate with MPH data and integrate with TechSpec

- design a material substitution system: subsdtitution rules, material database, queries

- implement interactive system for extracting technical specifications and constraints

- demonstrate redesign based on manufacturability (pilot)

Technical Data Requirement

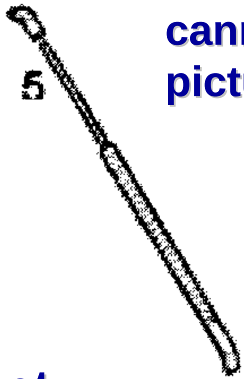
Geometric data is necessary but not sufficient for reverse engineering. We also need

- material data
- surface quality data
- heat treatment
- surface treatment
- precision data (tolerance information)

Part drawings may have this data, physical parts may not carry this info

What more do we need to know?

What is the function of this part →

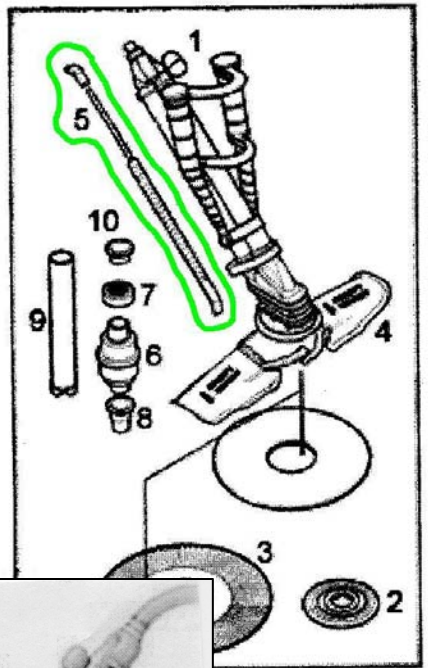


cannot tell by looking at just a picture, drg, or physical part

<u>Observation</u>

Part geometry (from drawing, physical part) is insufficient to understand function of a part unless it is a standard component

Mechanical parts move, transmit force, transmit/convert/absorb energy, allow/prevent material flow …

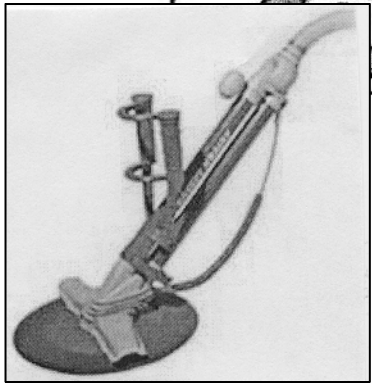


<u>Observation</u>

Viewing the part in relation to other components gives more information, but

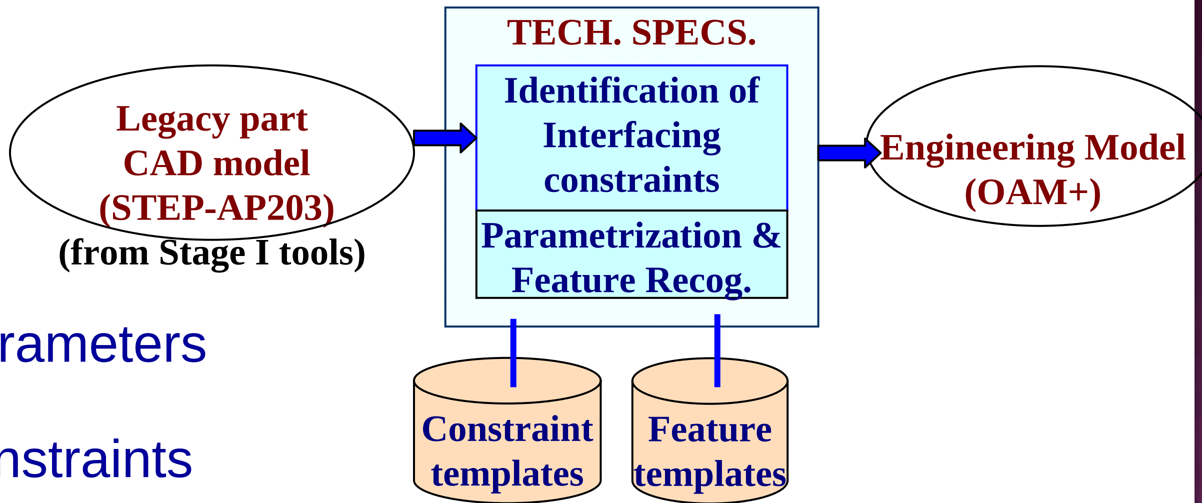
-we need to see it in its operating environment

-we need to apply technical expertise relevant to that domain



TechSpec Module

From the the assembly and part models extract:



- **Part geometry**
  - CAD model
  - Part features
  - geometric parameters
- **Constraints**
  - Assembly constraints
    - Mating regions
    - Shape, size
    - Spatial
  - Kinematic constraints
- **Loads**
  - External loads
  - Transfer loads
- **Supports**
- **Material specification, including HT**

Kinematic & Structural function

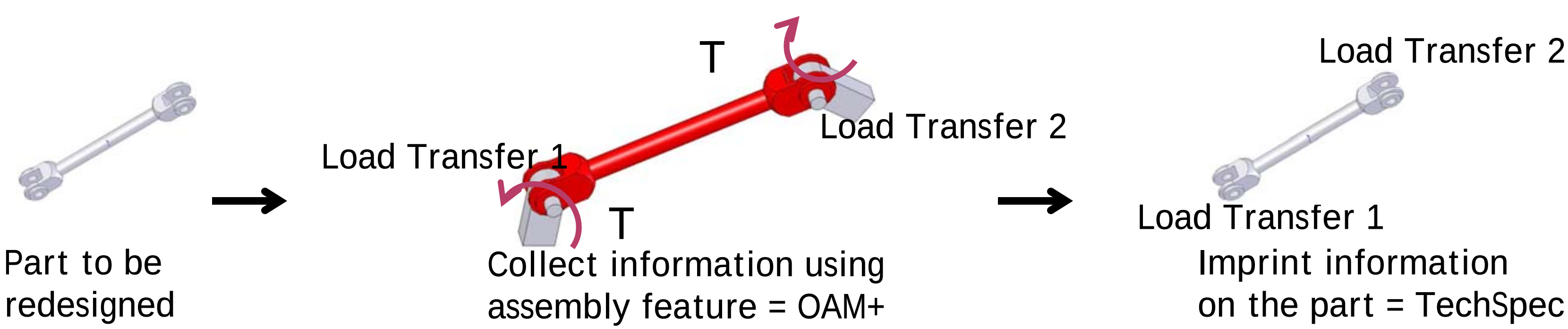
- **To completely characterize the state of the constraint of an assembly**
  - state of mobility and constraint needs to be determined separately
  - Screw theory can be used to do this
- **Screw theory**
  - Determines the specific degrees of instantaneous freedom of mobility and/or directions of instantaneous overconstraint of a given part in the assembly
  - First developed by Sir Robert Ball[1;] A simplified approach to analyze assemblies is developed by Whitney[2]
  - A screw is a way of representing the motions that a rigid body can undergo or of representing the forces and moments exerted on it.
  - Screws representing
    - motion are called twists, $T = [\omega_x, \omega_y, \omega_z, v_x, v_y, v_z]$
    - forces are called wrenches , $W = [f_x, f_y, f_z, m_x, m_y, m_z]$
  - A twist or wrench matrix has
    - six columns
    - one to six rows, one for each degree of freedom being described

TechSpec Contents

- **Part feature**
  - Required to support redesign
    - Parametric modification
    - Feature replacement
    - Constraint modification
  - Required by assembly feature
  - Must be represented using N-Rep definition
    - Existing feature recognizers will be useful
- **Assembly feature**
  - Required to store information between part features
  - Helps during design validation
- **Parameters**
  - Used in part and assembly features
  - Allows parametric redesign
- **Constraints**
  - Used in part features
  - Allows constraint based redesign
  - Used for validating design
- **Kinematics**
  - Mobility of parts
  - Needed to maintain the kinematic validity
  - limits of kinematic motion
- **Load paths**
  - Magnitude, direction, location, time historty

TechSpec Input/Output

- **Input to TechSpec**
  - A representative assembly of redesign part
- **TechSpec system needs to**
  - Extract interfacing, kinematic constraints
  - Define parameters, kinematic limit
  - Specify loads
- **Information are stored in OAM+**
- **The output is expressed in XNRep schema for redesign**



Part → Part + Assembly + AssemblyFeature = OAM+ → (OAM+) - Assembly = TechSpec

TechSpec Data Model development (OAM+)

- **Assembly feature is a must**
  - Part feature and information between them
- **Assembly can be viewed as**
  - Parts with some surface contacts
    - Simple
    - Only stores surface contact information
  - Parts with interacting part features (asm. feature)
    - Little more complex
    - Part features must be identified first – feature recognizers
    - Can store any information between the part features
    - Very useful for “imprinting”
      - The external part can be discarded after constraint extraction
      - New part can be replaced and constraints can be restored

Data Model Development - 2

- **Parameters - defines a new vraiable**
  - Between geom. Entities – geom. parameter
  - Between other params – algebraic parameter
  - Unlike constraint it does not put limit
  - Important for constraint spec. and redesign
- **Constraints representation**
  - Enumerated
    - Easy to use
    - Introduction of new constraint will need modification of the model – not flexible
  - Generic
    - Any two entities can be taken together and related to each other
    - Very flexible – new constraints can be defined and added
    - Can work with user defined constraints and features (NRep)
    - Can be translated to solve by constraint solver

ASU

DAL Design Automation Laboratory

Data Model Development - 3

- **Kinematics representation**
  - Screw theory is used
  - Opens up many possible automations
    - Kinematics extraction from interfacing constraints
    - Simple kinematic validation
    - Assembly hierarchy generation
- **Load Representation**
  - Equivalent load on a common mating point
    - Parts contact over a surface, not a point
    - Equivalent load may not represent the actual load correctly
      - Contact load transfer, multiple contacts
    - OAM+ is a model not an application – should only store the load
  - Actual load and load transfer information
    - The load and its location in redesign part co-ordinate system
    - The load transfer can be determined by the wrench matrix
    - Simple and accurate

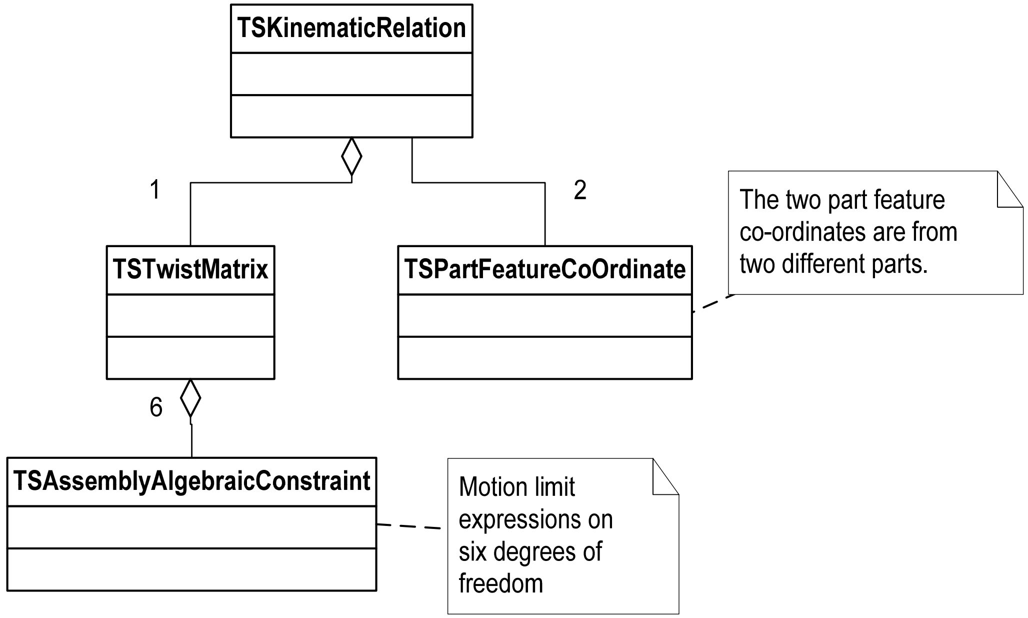
Data Model Development - 4

- **Base entity - TSFeatureEntity**
  - Points to a geometric surface
  - Features and their relations are defined using surfaces
  - Can be extended to support other entities in future
- **Geometry – TSPartGeometry**
  - Hides the internal geometry from user
  - Any BRep CAD model can be used internally
  - Application (TechSpec) should provide method
    - to traverse the geometry
    - to create references to the surfaces
  - ACIS commercial geometric kernel is used in this research

Data Model Development - 5

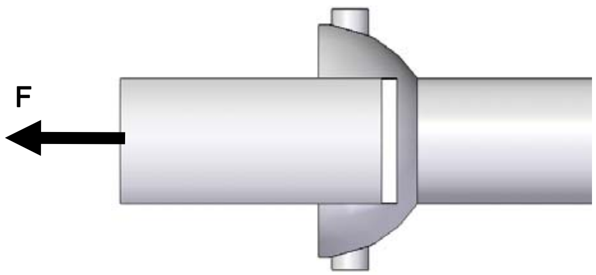
- **Material Representation - TSMaterial**
  - Set of material properties
  - Instead of using an array of numbers any material property can be created and added to the material
  - Flexible – can work with any material database (provided that the material property definitions comply)
- **Material property – TSMaterialProperty**
  - From the commercial material property definition
    - Property name
    - Variability (constant/function)
    - Value
    - Unit

Kinematic Relation

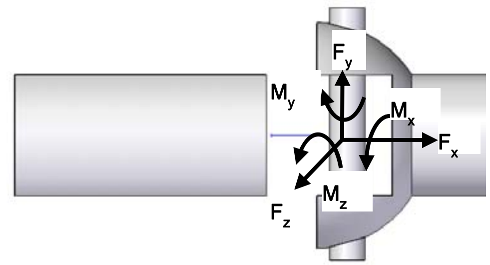


- *TSKinematicRelation* **is composed of a T*STwistMatrix* (from Screw Theory) and has two *TSPartFeatureCoOrdinates*.**
- **The two part feature co-ordinate systems should come from part features on two different parts**
- **The twist matrix describes the degrees of freedom in terms of possible angular and linear displacement**
- **Each DOF is associated with motion limits that are essentially algebraic constraints**
- **Expressing limits as algebraic expression in terms of part and assembly parameters, instead of a specific limiting value, assures that the limits remain valid when the design is changed.**

Transfer Load



External load



Transfer load acting on load point

- **TSTransferLoad is the load transferred between parts in an assembly.**
- **TransferLoad should be placed on an assembly feature, the common portion of the mating parts in an assembly.**
- **The concept of LoadPoint is used to specify the transfer load.**
- **LoadPoint is a point near the common mating position of an assembly feature, where all the loads due to a load transfer can be assumed to be acting**
- **LoadPoint is a point near the common mating position of an assembly feature, where all the loads due to a load transfer can be assumed to be acting**
- **One advantage of the notion of load point is it can be imprinted onto the part to be redesigned**

Loads

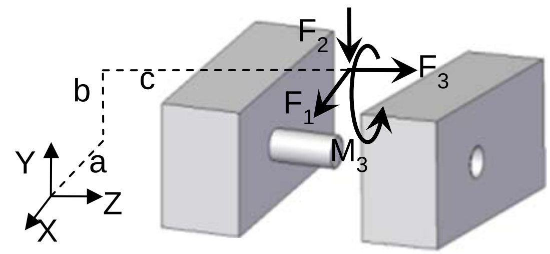
- **Loads on part**
  - External (applied)
  - Internal (stress calculation, needed by simulation app.)
- **Force or moment**
  - Location – function of time x(t), y(t), z(t)
  - Magnitude – function of position and time x, y, z, t
- **The load vector:**

$$P = \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_{xy} \\ M_{yz} \\ M_{zx} \end{bmatrix} \text{ where } P_i = f(x, y, z, t)$$

- **From the stress equation, its calculation will need:**
  - Surface contact – present in assembly feature
  - Amount of surface mate
  - Load transfer – wrench matrix
- **Amount of surface mate**
  - Obtained from geometric intersection of mating surface
  - Represented by a list of mating surfaces S_i and their bounding edges E_i : MM = (S_i, E_i)

Loads - 2

- **Static load on an assembly**
- **The load vector (based on screw theory)**
  - $F = [F_1\ {-F_2}\ F_3\ 0\ 0\ M_3]^T$
- **The location L = (a,b,c)**
- **Mating Matrix**
  - A surface fragment on the pin (redesign part)
  - Two edges bounding it
  - $MM = \{(S_1), (E_1,E_2)\}$
- **Load transfer**
  - Wrench matrix for pin-hole feature
  - Represents – forces/moments experienced by the joint
  - Can be derived from twist matrix
  - For this example

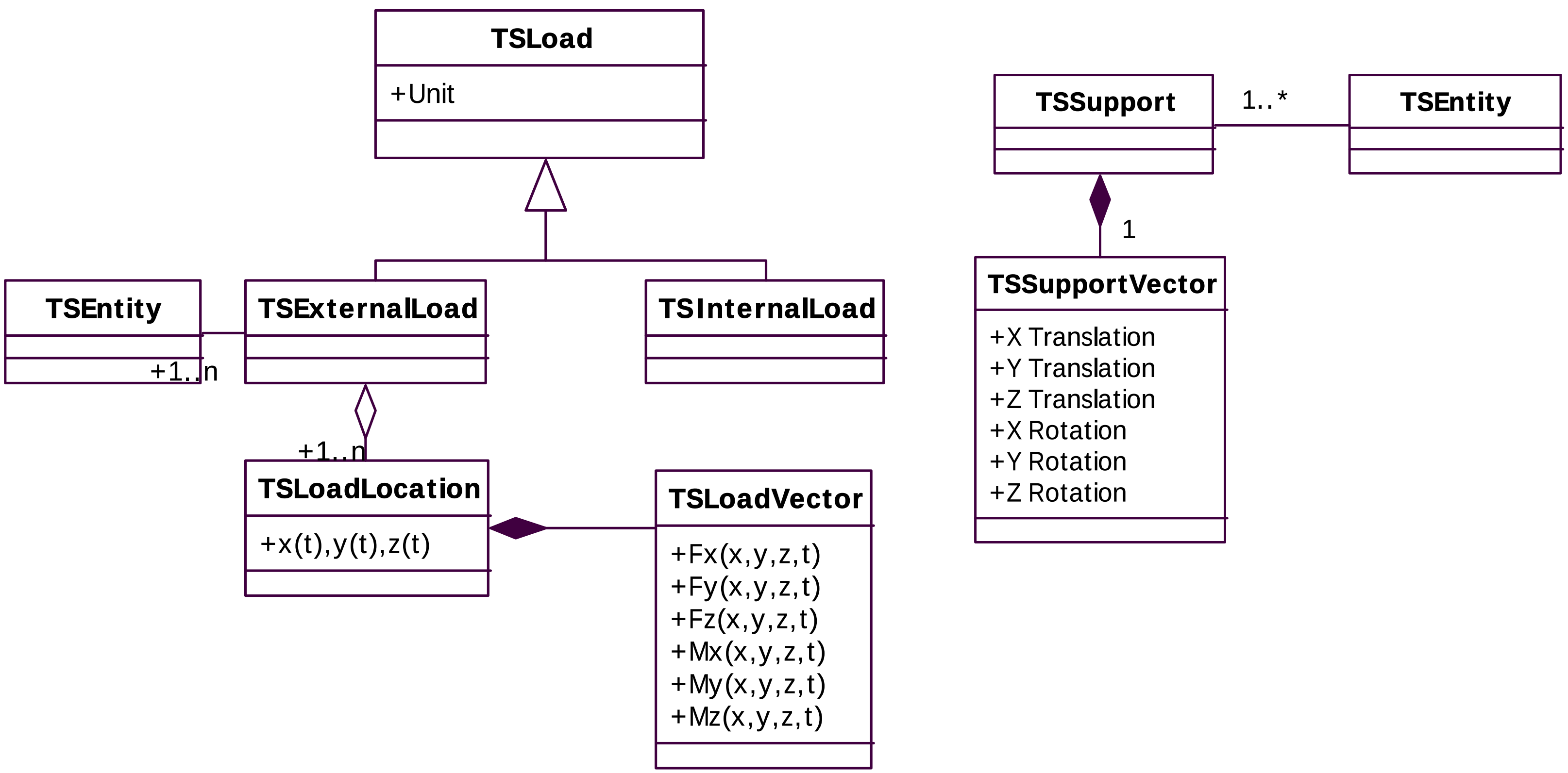


$$W = \begin{bmatrix} F_x & 0 & 0 & 0 & 0 & bF_x \\ 0 & F_y & 0 & 0 & 0 & aF_y \\ 0 & 0 & F_z & 0 & 0 & 0 \\ 0 & 0 & 0 & M_x & 0 & 0 \\ 0 & 0 & 0 & 0 & M_y & 0 \end{bmatrix}$$

$$LoadTransferred = \begin{bmatrix} F_1 & 0 & 0 & 0 & 0 & bF_1 \\ 0 & -F_2 & 0 & 0 & 0 & -aF_2 \\ 0 & 0 & F_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

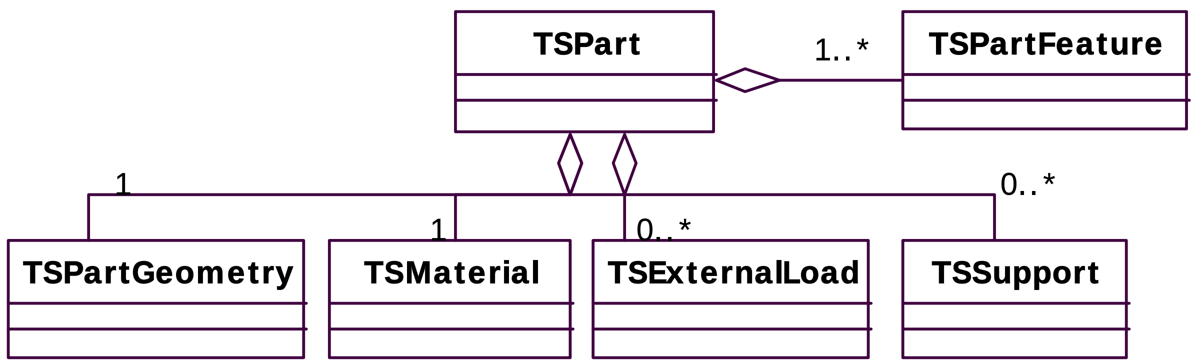
Load Representation

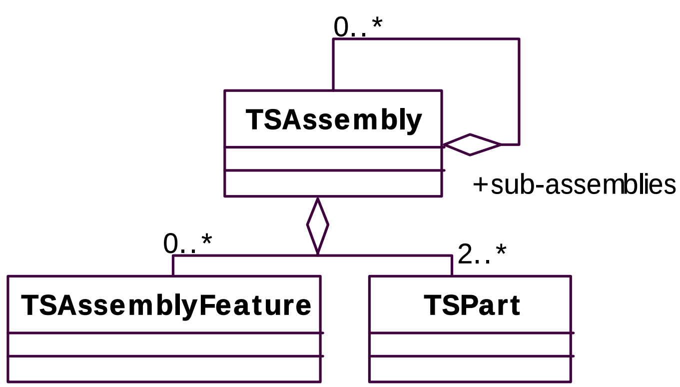
- **Structural support**
  - On edge, vertex or surface
  - Limits linear or rotational motion
  - For stress analysis
- **A vector contains limiting values and their units**



Parts & Assembly Model

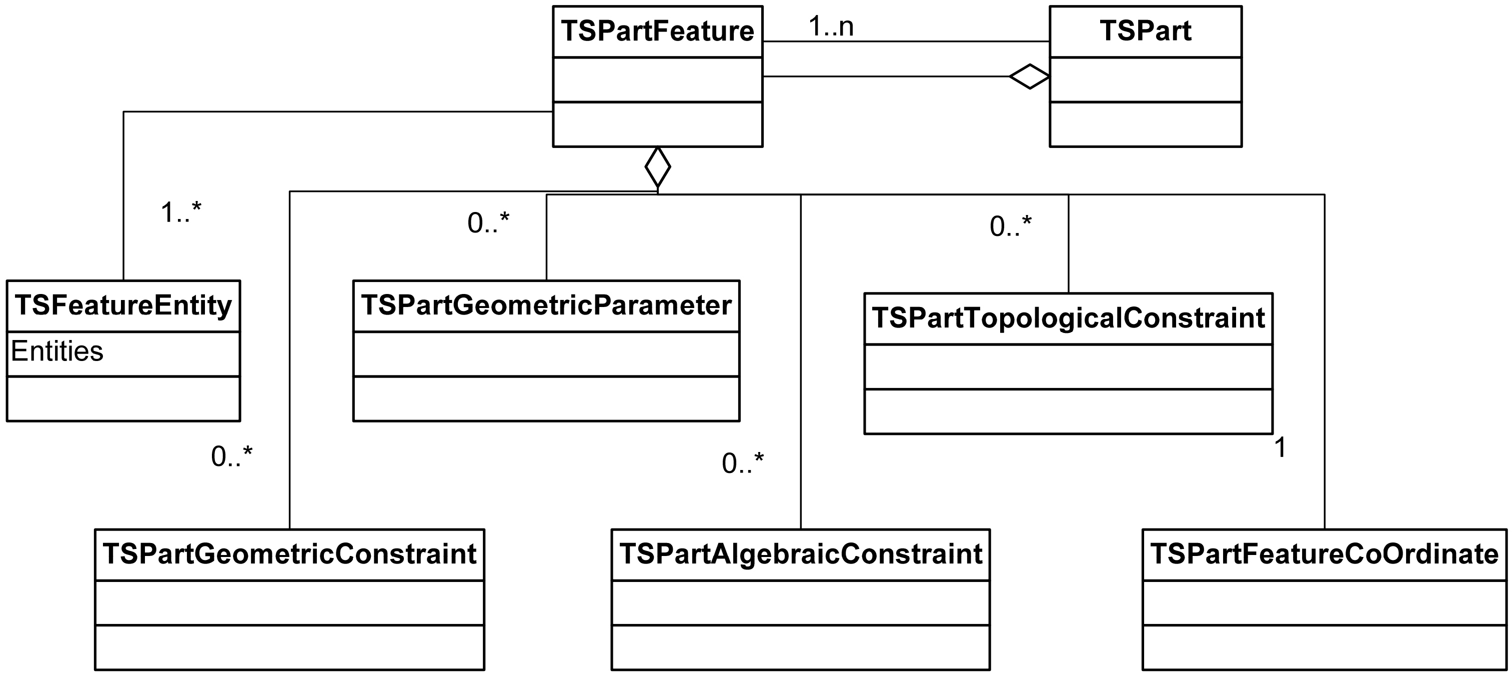
- Part can have geometry, material, load and support
- Functional & behavioral attributes and tolerances are excluded as discussed before
- Part features are added for redesign support
- Assembly contains parts, sub-assemblies, assembly features
- Assembly feature contains the relations between part feature





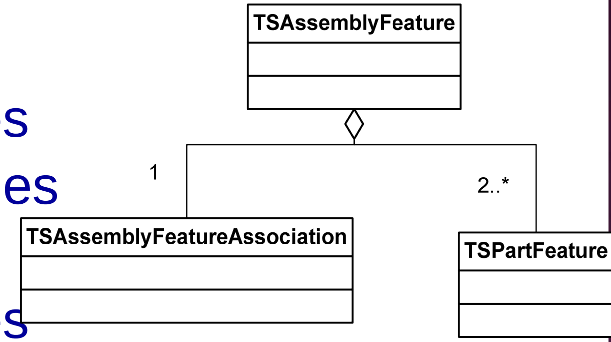
Part Features

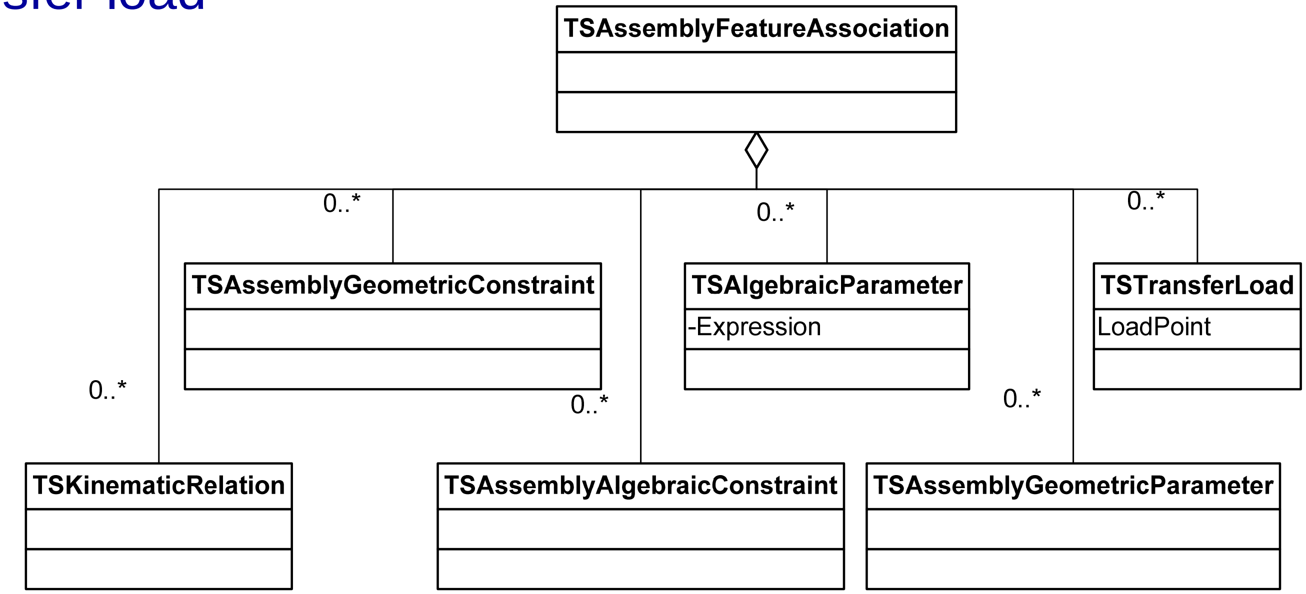
- **Features are of two types**
  - Part features – TSPartFeature
  - Assembly features – TSAssemblyFeature
- **Part feature**
  - Mimics the N-Rep definition: geometry, geometrical relationship, topology, topological relationship, parameters, parametric relationship, location
  - Application independent, user defined



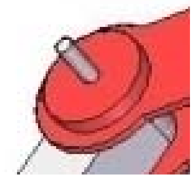
Assembly Features

- **An equivalent NRep definition for assembly feature**
  - Part features
  - Parameters
    - Geometric – between geometric entities
    - Parametric – between parametric entities
  - Constraints
    - Geometric – between geometric entities
    - Algebraic – between parametric entities
  - Kinematics
  - Transfer load

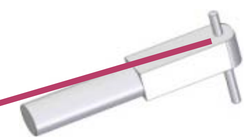




Assembly Feature

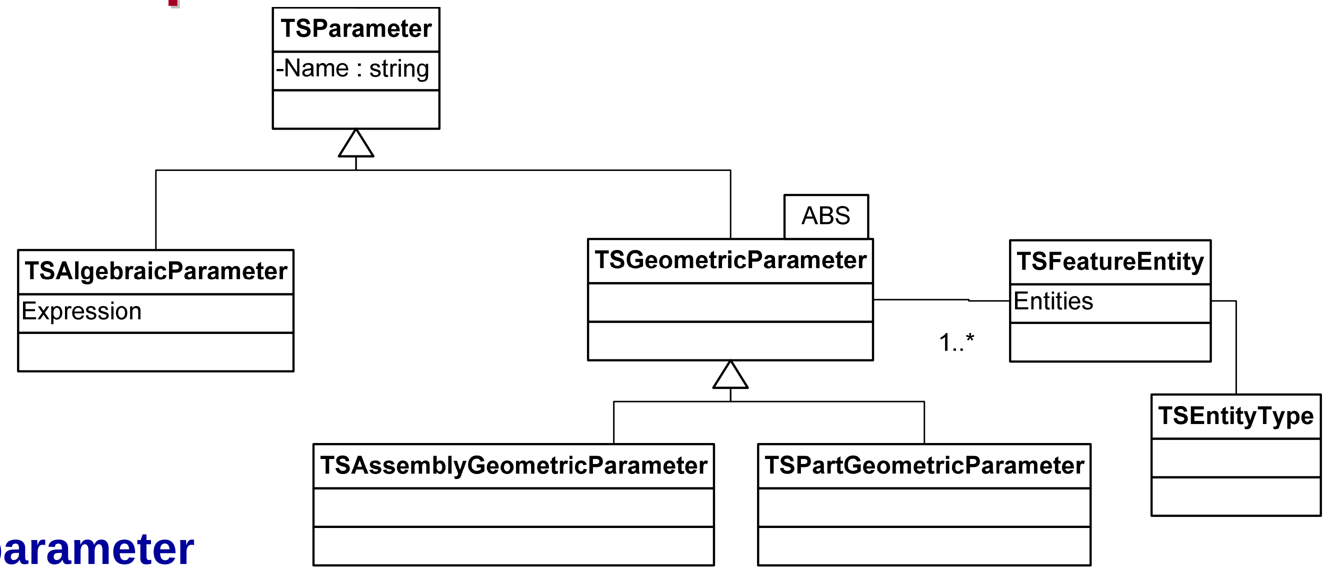


- TSAssemblyFeature — Name: Shaft1Tab-LinkSlot1
  - TSPartFeature
    - Name: Tab1 — Part: Shaft1
    - Name: Slot1 — Part: Link
  - TSAssemblyFeature Association
    - TSAssemblyGeometric Constraint
      - Name: Parallel — Faces: Face4 on Tab1 and Face10 on Slot
      - Name: Coincident — Faces: Face1 on Tab1 & Face14 on Slot
      - Name: Coincident — Faces: Face2 on Tab1 & Face15 on Slot
    - TSAssemblyGeometric Parameter
      - Name: Clearance — Faces: Face4 on Tab1 and Face10 on Slot1
    - TSTransferLoad — Forces Fx, Fy, Fz and Moments Mx, My, Mz
    - TSKinematicRelation — T = [0]



- TSAssemblyFeature — Name: Pin1-Shaft1Hole
  - TSPartFeature
    - Name: PinFeature1 — Part: Pin1
    - Name: Hole1 — Part: Shaft1
  - TSAssemblyFeature Association
    - TSAssemblyGeometric Constraint
      - Name: Concentric — Faces: Face1 on Pin1 and Face7 on Shaft1
    - TSAssemblyGeometric Parameter
      - Name: Clearance — Faces: Face1 on Pin1 and Face7 on Shaft1
    - TSTransferLoad — Forces Fx, Fy, Fz and Moments Mx, My, Mz
    - TSKinematicRelation — T = [ω_z υ]

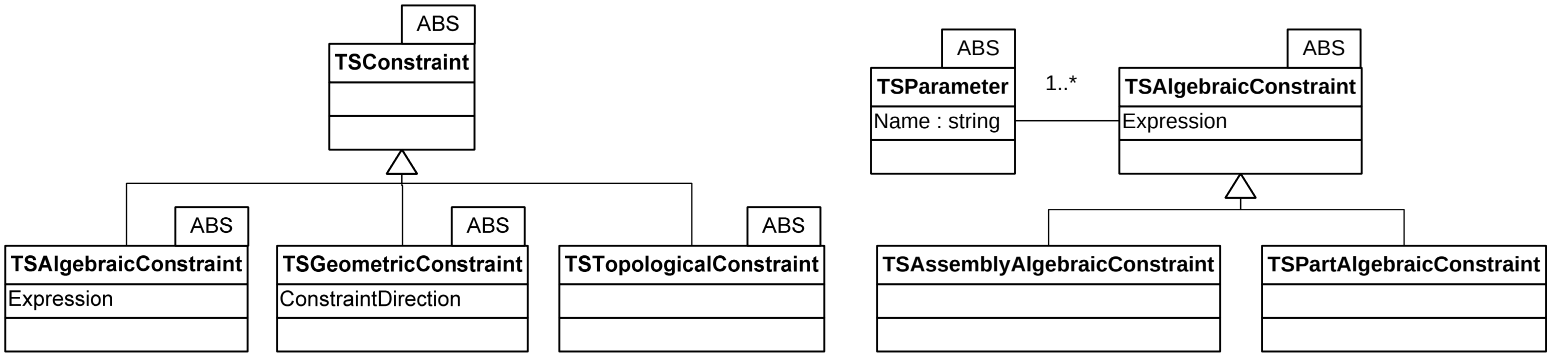
Parameter Representation



- **Geometric parameter**
  - defined by a geometric entities
  - Example: Distance, Radius
- **TSPartGeometricParameter**
  - Parametric relation on a part
  - Example: Distance between two faces, d = face2 – face1
- **TSAssemblyGeometricParameter**
  - Parametric relation on two different parts
  - Example: Distance between two faces on different parts, d = part2:face1 – part1:face1
- **Algebraic parameter**
  - defined by an algebraic expression
  - Example: Clearance between concentric cylinders, c = d2 – d1

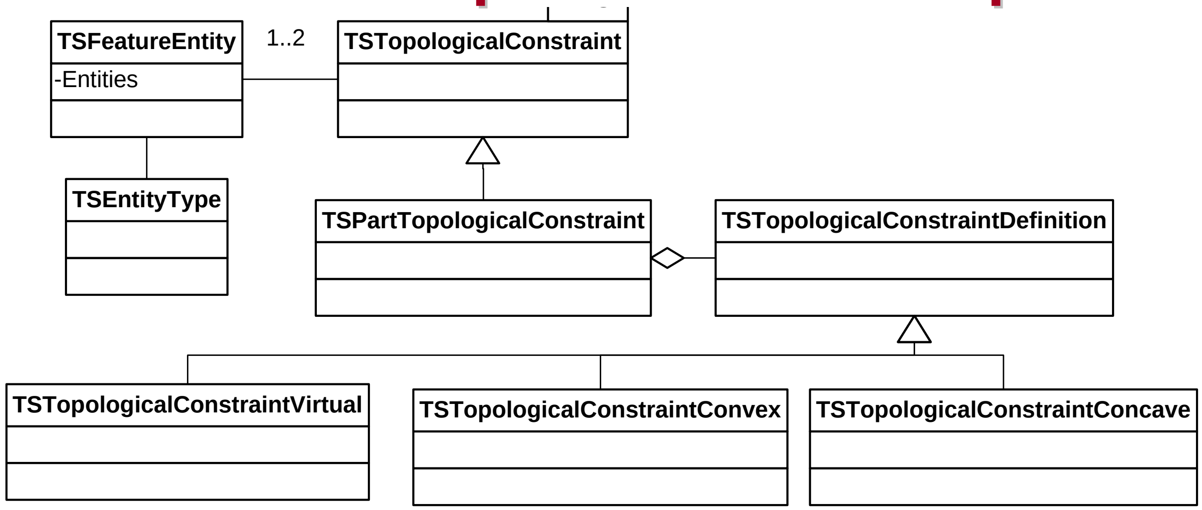
Design Automation Laboratory

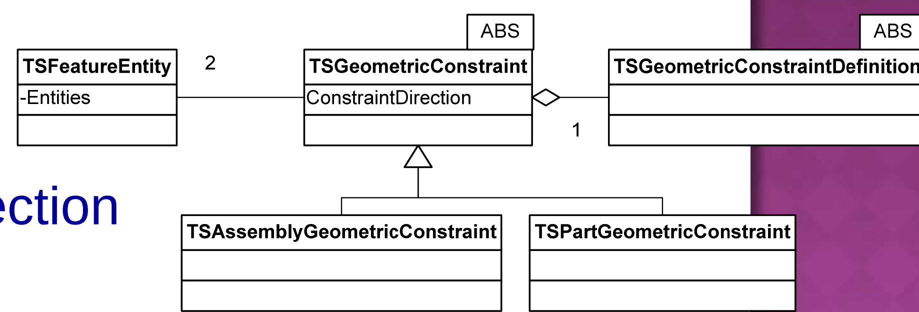
Algebraic Constraint Representation



- **Constraint puts**
  - absolute or relative limit on existing
    - parameters, locations, orientations and size of geometric entities
- **TSAssemblyAlgebraicConstraint**
  - Represents assembly algebraic constraints
  - Example: Diameters of two pin should be same, d1 == d2
- **TSPartAlgebraicConstraint**
  - Represents part algebraic constraints
  - Example: Clearance must be less than a value, c <= 0.1mm

Geometric/Topo Constraint Representation





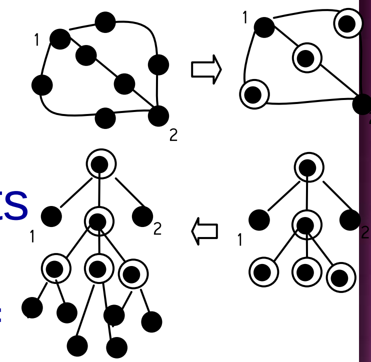
- **ConstraintDirection**
  - indicates geometric constraint direction
  - Example: 1-2, 2-1 or none
- **TSGeometricConstriantDefinition**
  - Represents coincident, concentric etc.
  - Example: Distance between two faces should have a minimum value 0.1
- **TSTopologicalConstraintDefinition**
  - Represents virtual, convex and concave constraints

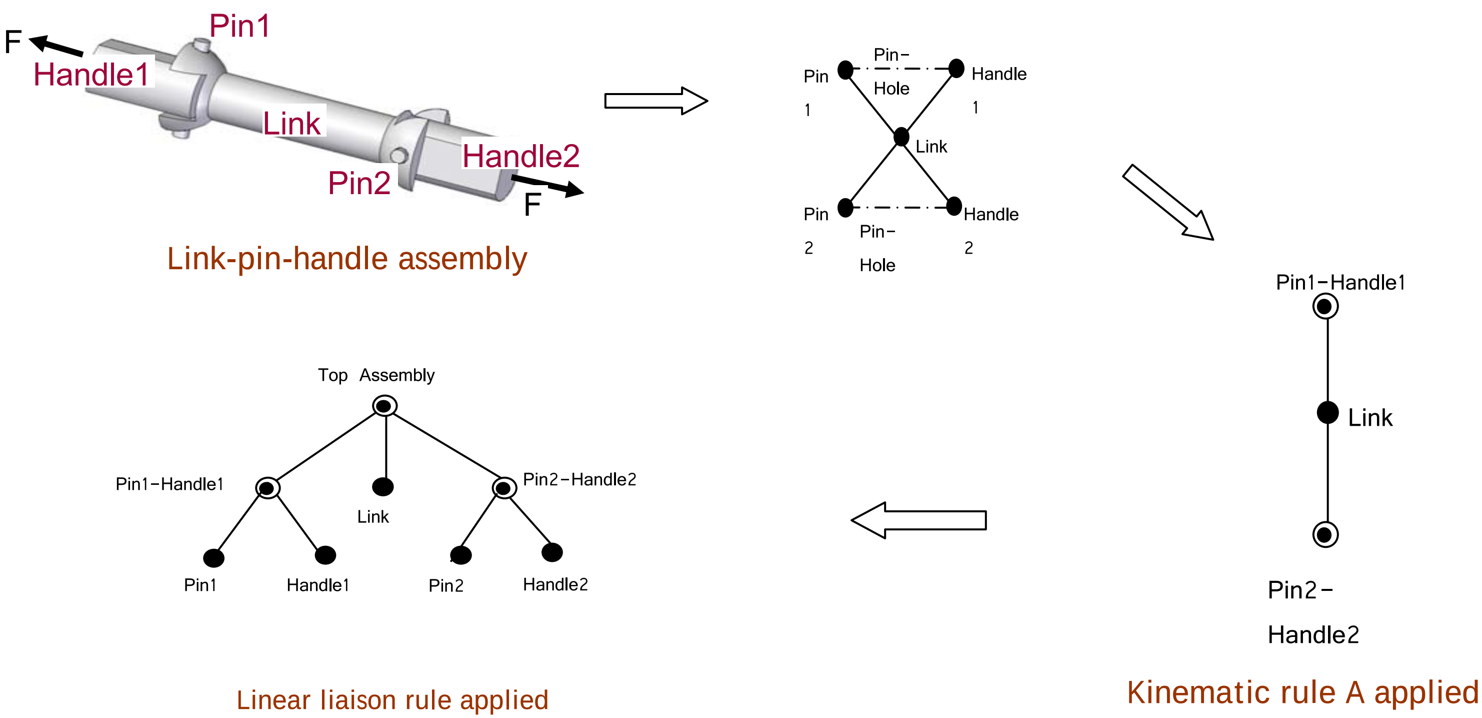
Automated Tasks in TechSpec Module

- **Kinematic constraints extraction from surface contact**
  - Define “basic surfaces” – plane, cylinder, sphere
  - Define possible contacts – plane-plane, plane-cylinder
  - Derive screw for these contacts
  - Build screw matrix of any feature by combining the screw matrix of the basic surface contacts
- **Simple validation of mobility**
  - Screw matrix in conjunction with network analysis
  - Finds degrees of freedom a part has wrt. other parts
  - Can be used for quick check on kinematic mobility

Automated Assembly Hierarchy Generation

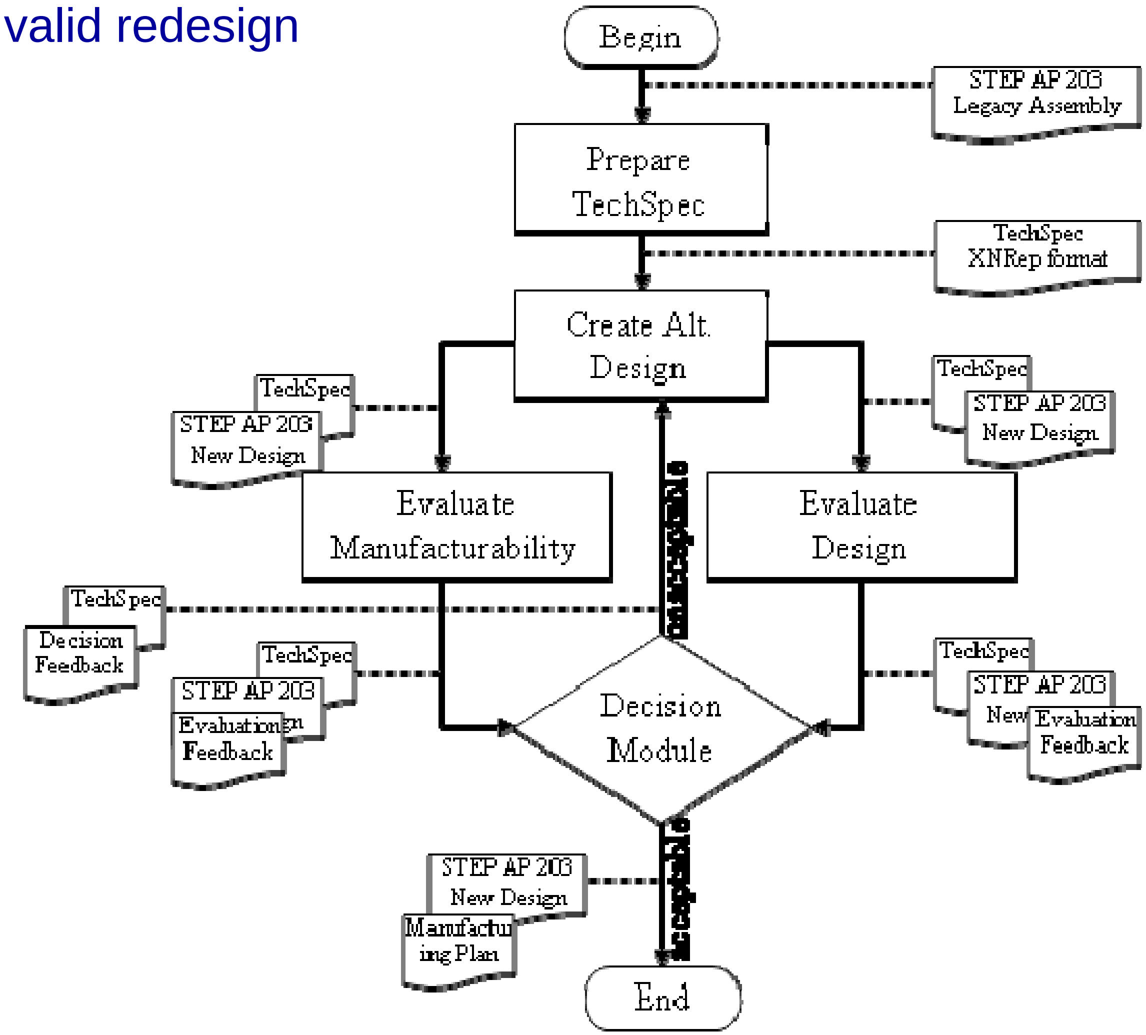
- Based on kinematic hint
- Relative effect the redesign part has in the assembly
  - If root of the assembly – effect sub-ordinate parts
  - If not root – other parts may not be effected
  - Note – surface contacts should be taken care of
- Rule based enhanced liaison graph decomposition





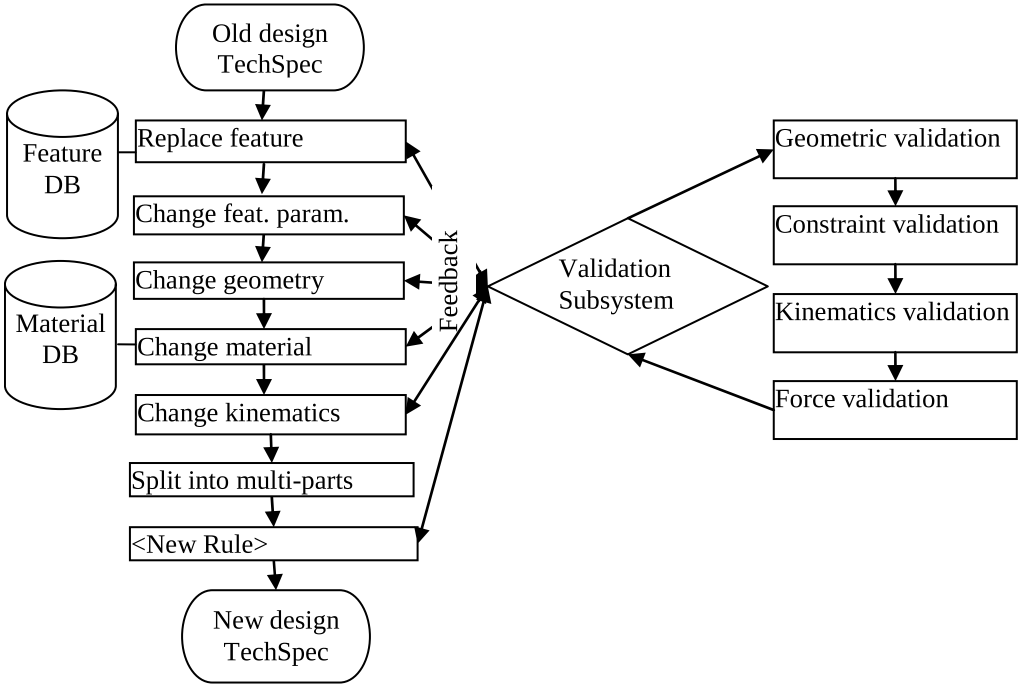
Iterative ReDesign

- Iterative redesign contains the five components of rapid re-engineering system
- More redesign iteration = more time
- Important – apply some redesign rules
  - Should produce valid redesign



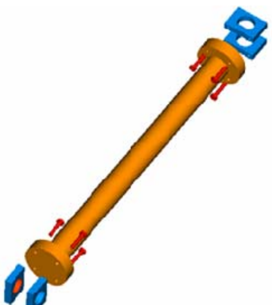
ReDesign Rules

- **Two approaches**
  - Complete redesign then validate
  - Incremental redsign and immediate validation
- **Second approach is better**
  - Eliminates iteration
  - Produces valid redesign
  - Problem: the validation may take time

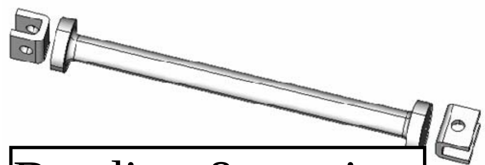


ReDesign Rule Example: Break into multiple parts

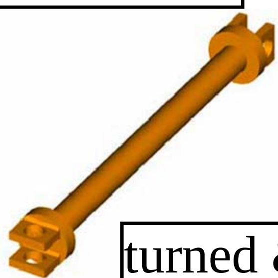
- Can simplify manufacturing process
- Non-working simpler sub-component can be replaced faster
- Validation is not possible – redesign is targeted for assembly



turned & milled - bolted



Bending & turning - bolt/weld

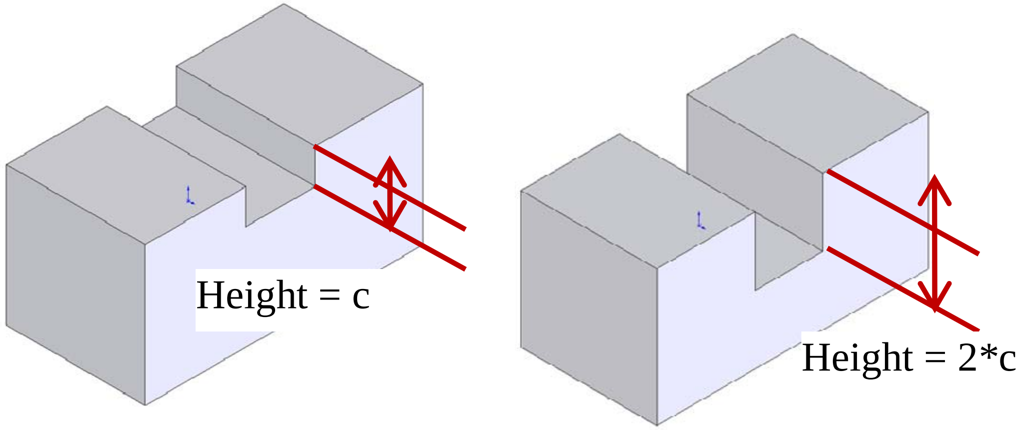


turned & milled - welded

turned & milled - bolted

turning - bolt/weld

ReDesign Rule: Parameter change



- **Constraint checking must be performed**
- **Requires 3D constraint validation**
  - Does not have the history
  - Can not rollback to 2D sketch and update
- **Redesign and validation**
  - User triggers the procedure by specifying the parameter edit request
  - A list of available parameters is presented to the user
  - User selects the parameter and types in the new value
  - Constraint solver is called for new value of the parameter
  - Design changes from the new constraints set are applied

Implementation

Process Flow

1. Part Feature specification
Specify part feature definition by means of Nrep language. This part feature definition can come from application like Nrep Feature Tutor.

2. Assembly Feature specification
Combine two or more part features into assembly features. Fill in assembly feature information in OAM+

3. Loading Assembly and Parts
Load the part. Create one or more TSPart and TSAssembly instances and fill into OAM+.

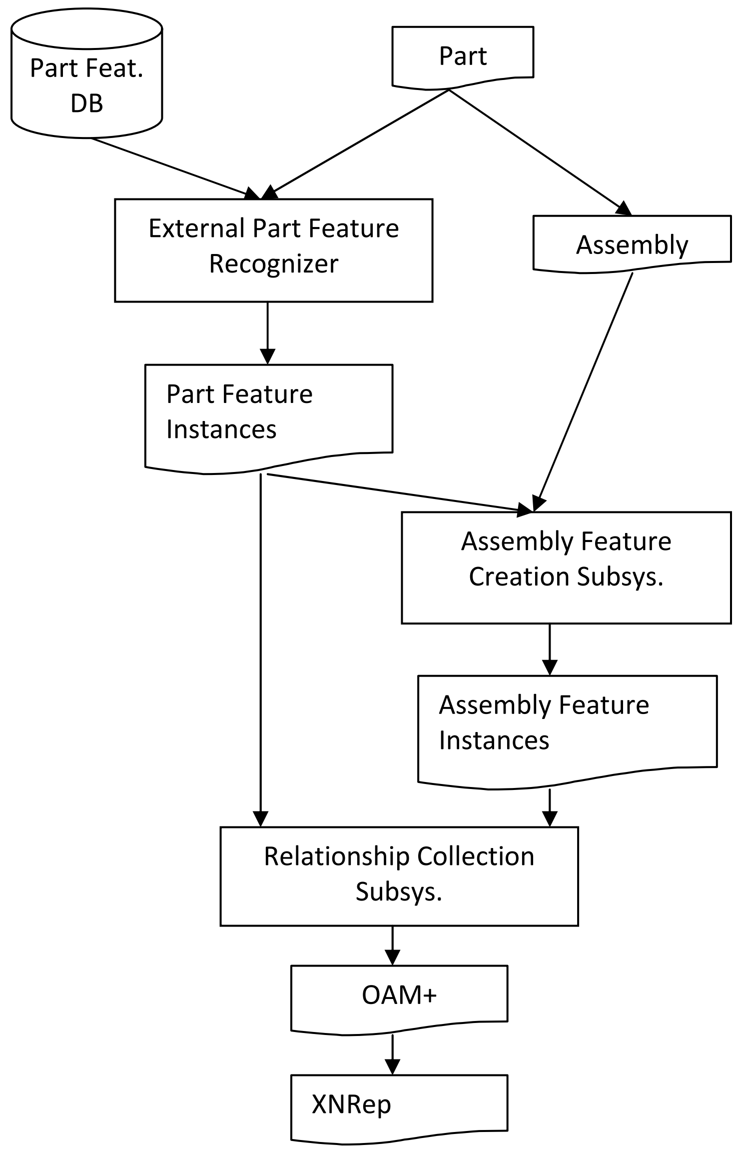
4. Part and Assembly feature recognition
Call external or internal feature recognizer and get the instances of part features. Create TSPartFeatures instances from it and insert into OAM+. Also provide an assembly feature recognizer interface/feel for specifying the assembly feature instances consisting the part feature already obtained. Insert these TSAssemblyFeatures into OAM+.

5. Constraints and load specification
Provide an interface for specifying constraint and loads. Create several subclasses of TSConstraint and add them into OAM+.

6. Validate constraints
Call external library such as DCM for the constraint validation.

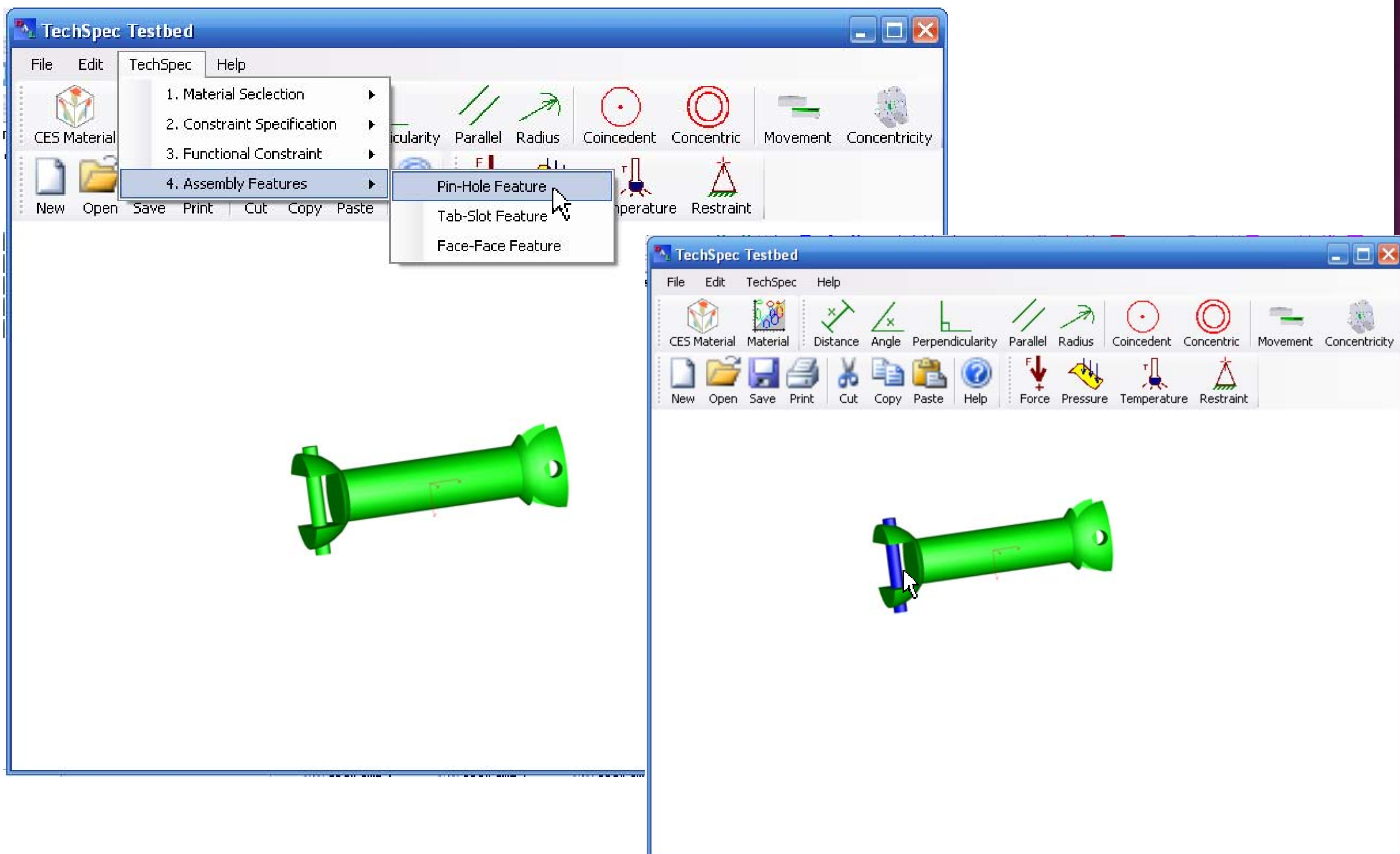
7. Produce TechSpec
The procedure to produce TechSpec from OAM+ is yet to be defined.

Module interaction



TechSpec Demo System

Import CAD files → Interactive part & asm feature defn → TechSpec Templates → Export OAM+



Assembly Feature Recognition

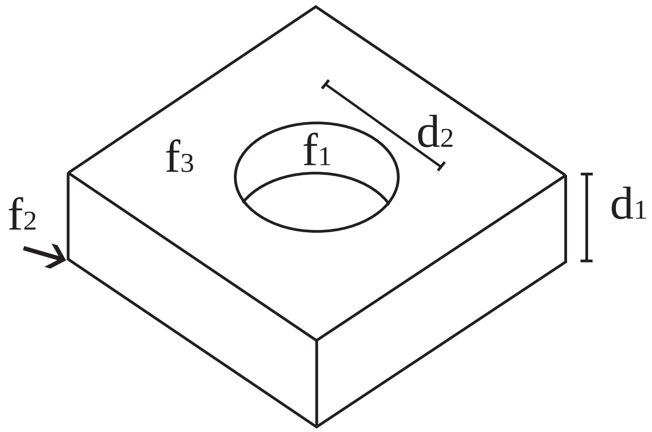
- **Part Feature Definition**
  - Before attempting to go into detail with assembly features, it is important to understand the basics that are involved in assembly features.
  - Assembly features primarily depend on individual part features and the relationships between these part features.
  - Before an assembly feature can be created, individual part features must be identified and recognized.
  - Because of the lack of good part feature recognizers, interactive user-defined feature recognizers were created in ASU's Design Automation Lab (DAL) to fulfill the needs of its user.
  - Currently have prismatic and turning feature recognizers.

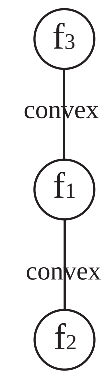
Assembly Feature Recognition

- **Part Feature Definition**
  - The following part feature template defines a part feature:
    - Topology (real and virtual faces)
    - Topological Relationships (edge convexity relation)
    - Geometry (face types: planar, cylindrical, etc.)
    - Geometric Relationships (parallel, perpendicular, coaxial, etc.)
    - Parameters (typically dimensions defined by geometric relations or attributes)
    - Parametric Relationships (derived parameters or constraints on parameter values)

Assembly Feature Recognition

- **Example of Part Feature Definition**
  - Part Feature template for Round Hole:
    - Topology
      - Real Face: “side” f1
      - Virtual Faces: “Vbottom” f2, “Vtop” f3
    - Topological Relationships
      - Edge “convex”: f1 & f2; f1 & f3
    - Geometry
      - Planar faces: “Vbottom” f2, “Vtop” f3
      - Cylindrical face: “side” f1
    - Geometric Relationships
      - Constraint “parallel”: f2 & f3
      - Constraint “perpendicular”: f1 & f2
    - Parameters
      - Parameter “hole_depth”: d1 = distance (f2, f3)
      - Parameter “hole_dia”: d2



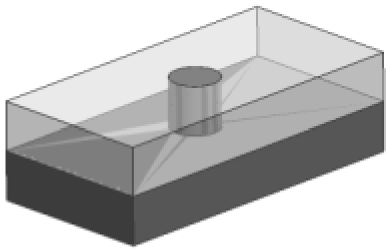
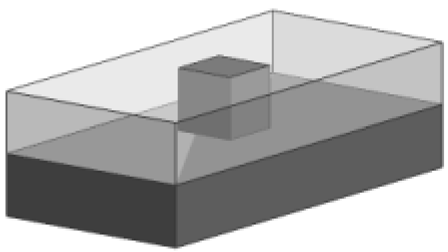
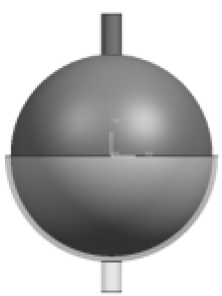


Assembly Feature Recognition

- **Assembly Feature Definition**
  - The next step is to create an assembly feature template similarly to that for part feature recognition.
  - The following template defines an assembly feature:
    - Part features that constitute the assembly feature
    - Assembly Parameter Definition
      - Geometric – parameter defined by two geometric entities directly
      - Algebraic – parameter defined by other parameters
    - Constraints / Relations
      - Geometric – constraint between two geometric entities
      - Algebraic – constraint between parameters
    - Kinematic Relation – DoFs and motion limits
    - Structural Relations: load point, component directions and magnitude, time functions

Assembly Feature Recognition

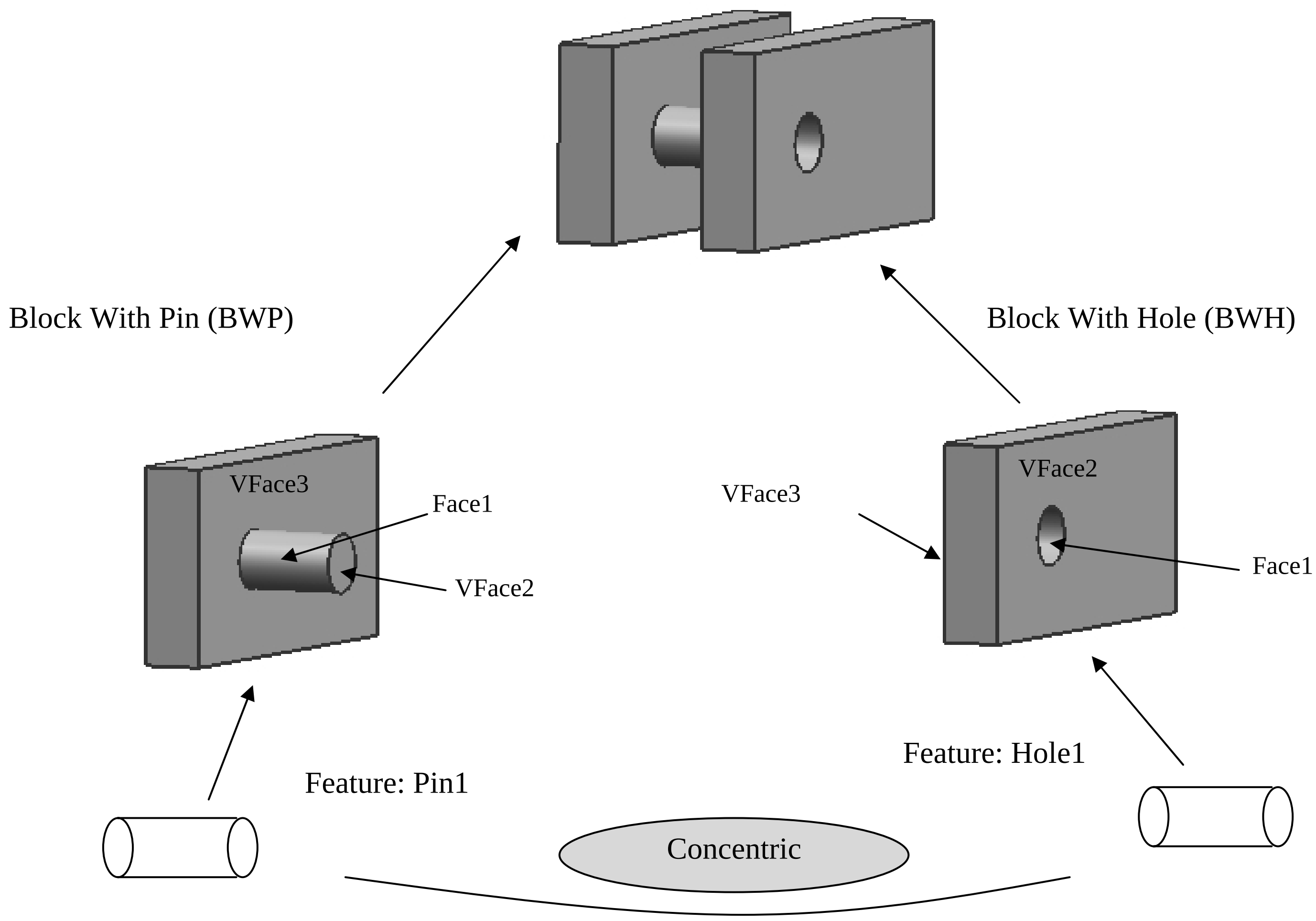
- **Examples of Assembly Features**

Assembly Featrue	Mating Relations and Constraints
Round Pin and Hole 	Pin top face against hole bottom face OR pin virtual face against hole virtual face Pin side face relations of the form: Against with clearance Diameter of pin side face < diameter of hole side face Pin length <= hole depth
Prismatic Pin and Hole 	Pin top face against hole bottom face OR pin virtual face against hole virtual face Pin 4 side face relations of the form: Against with clearance Width of side pin face < width of side hole face Pin length <= hole depth
Spherical Joint 	Ball face against socket face Ball face relations of the form: Against with clearance Diameter of ball face <= diameter slot face

Assembly Feature Recognition

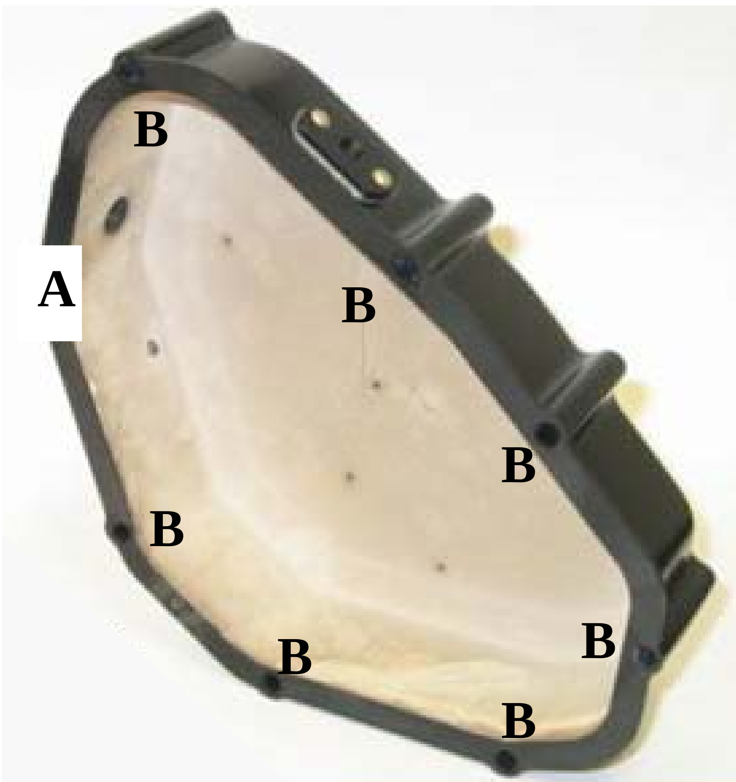
- **Example of Assembly Feature Definition (Pin and Hole)**
  - Part features:
    - Pin: “Pin1”
    - Hole: “Hole1”
  - Assembly Parameter Definition
    - Geometric
      - Eccentricity = distance between pin axis and hole axis
    - Algebraic
      - Clearance = hole_dia – pin_dia
  - Constraints / Relations
    - Geometric
      - Concentric: Face1 on BWP & Face1 on BWH
      - Against with clearance: Face1 on BWP & Face1 on BWH
      - Against: VFace3 on BWP & VFace3 on BWH
    - Algebraic
      - pin_dia < hole_dia
      - pin_length ≤ hole_depth

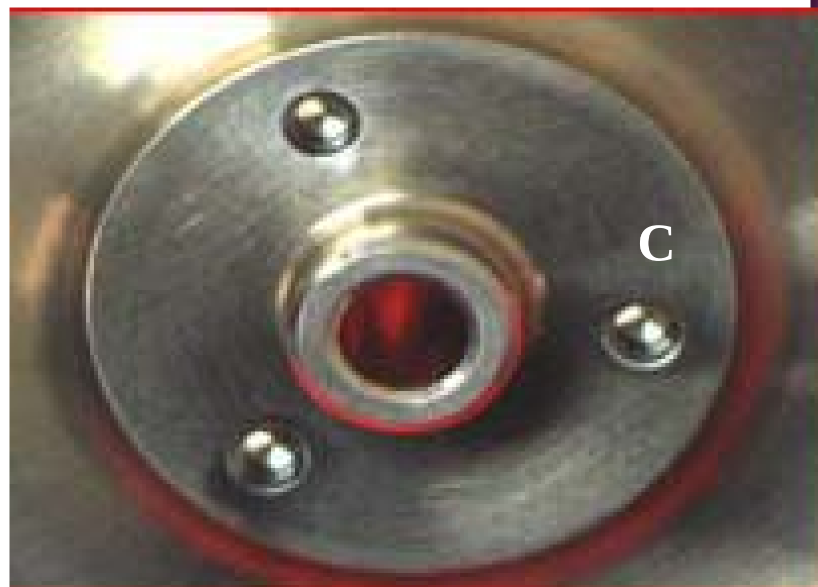
Assembly Feature Recognition



Assembly Feature Recognition

- **Legacy Part Specimens**
  - Plane to Plane (A)
  - Round Pin and Hole (B)
  - Spherical Joints (C)





Material Substitution Rules

- **Step One: Data Collection**
  - Determine the current material and gather necessary information associated with the existing part that is to be re-designed and its material.
    - Part material
      - Exact or partial knowledge
    - Failure mode (how the current part failed)
    - Part function
    - Loads (type, magnitude, direction)
    - Criticality of part (consequences of failure)
    - Manufacturing process (casting, machining, injection molding)
    - Part surface quality
    - Heat treatment process
    - Environment (temperature, chemical, etc)
    - Overall size

Material Substitution Rules

- **Step Two: Data Analysis**
  - Based on the gathered information in step one, critical properties can be obtained and populated.
  - Specific rules can be used to determine the critical properties of a part based on material type, manufacturing processes, part function, failure modes, etc.
  - In most cases, modes of failure can be used to identify critical properties of a given part.
  - In some cases, the user may not be able to determine the failure mode.
    - Failure mode can be determined by part usage or common failure modes associated with certain types of parts.
  - Critical properties can be identified based on the mode or modes of failure.

Material Substitution Rules

- **Step Three: Determine Goals and Constraints**
  - This step involves setting up material filters to find equivalent materials.
  - In this step, the user will have more control by inputting what materials are currently available for substitution.
    - Whether it is bar, sheet, or plate stock, pellets, etc.
  - The user also will be able to input available manufacturing processes.
    - Such as casting, machining, and injection molding.
  - Important pieces of data are to be determined, calculated, and stored.
    - Such as material indices of key properties (important ratios such as $S_y^{2/3}$/p, E/p, etc).
    - These values will be used later in the process to filter the available materials down to a group of candidate materials.

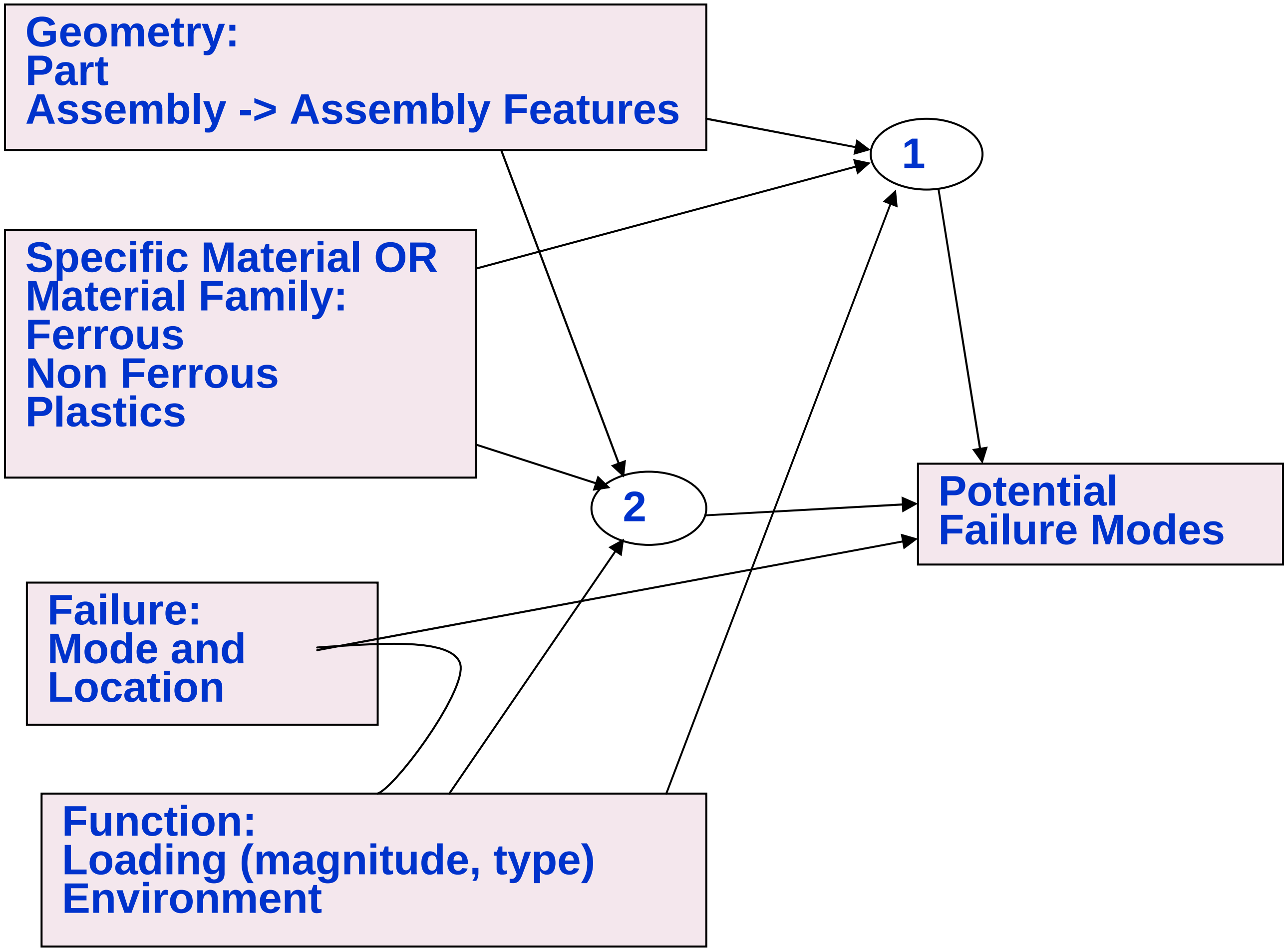
Material Substitution Rules

- **Step Four: Identification of Candidate Materials**
  - This step is where the relevant material properties data, for the current and candidate materials, are gathered and stored based on the information from the previous steps. These may be
    - Physical properties (density, ductility, etc)
    - Mechanical properties (strength, hardness, toughness, etc)
    - Electrical properties (conductivity, permittivity, etc)
    - Thermal properties (thermal conductivity, thermal diffusivity, specific heat, etc)
    - Environmental properties

- **It is important to note that typical properties will be used.**

MatSub Logic

- **The first scenario (labeled 1) is when the user knows geometry, material, and function.**
  - geometry can be used to obtain assembly features.
  - function can be used to determine potential failure modes.
- **The second scenario (labeled 2) is when the user knows geometry, material, and how it failed**
  - the input failure mode can be stored as a possible failure mode directly.



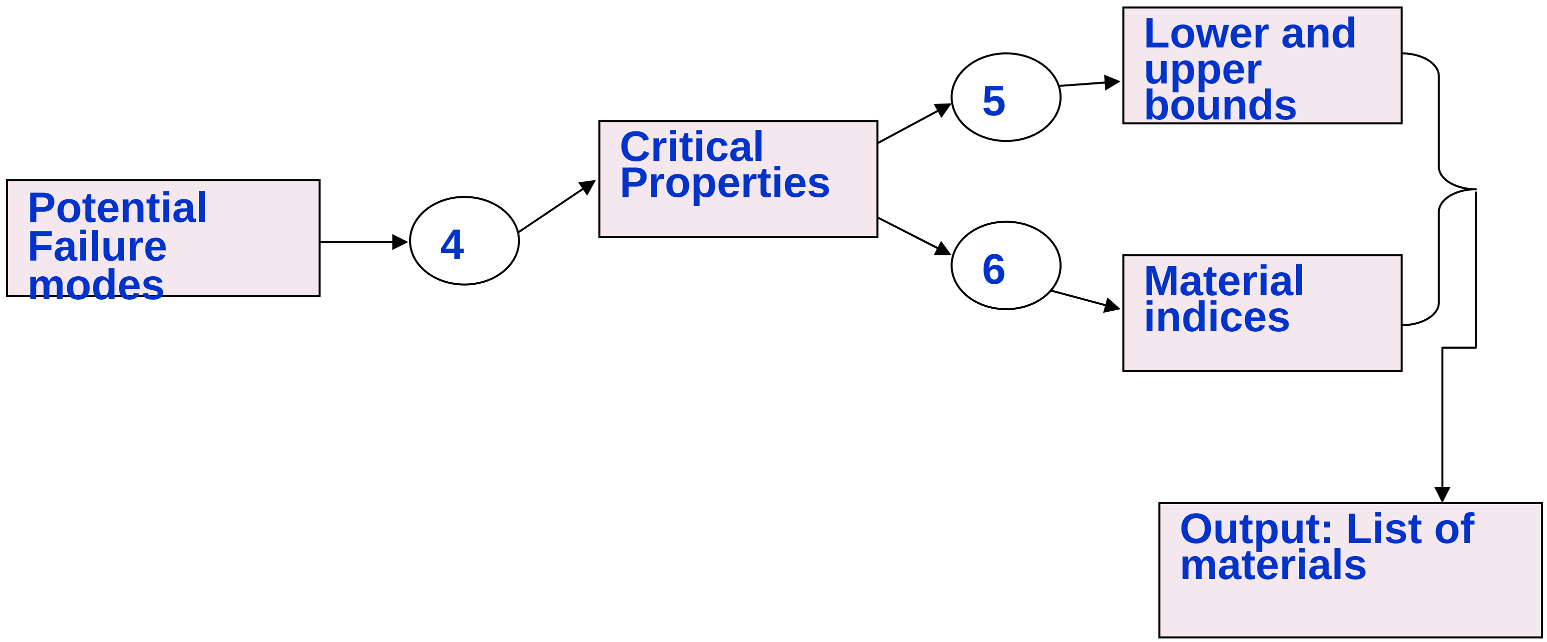
MatSub Logic

Once potential failure modes are discovered, it is necessary to determine the critical properties, lower and upper bounds and material indices.

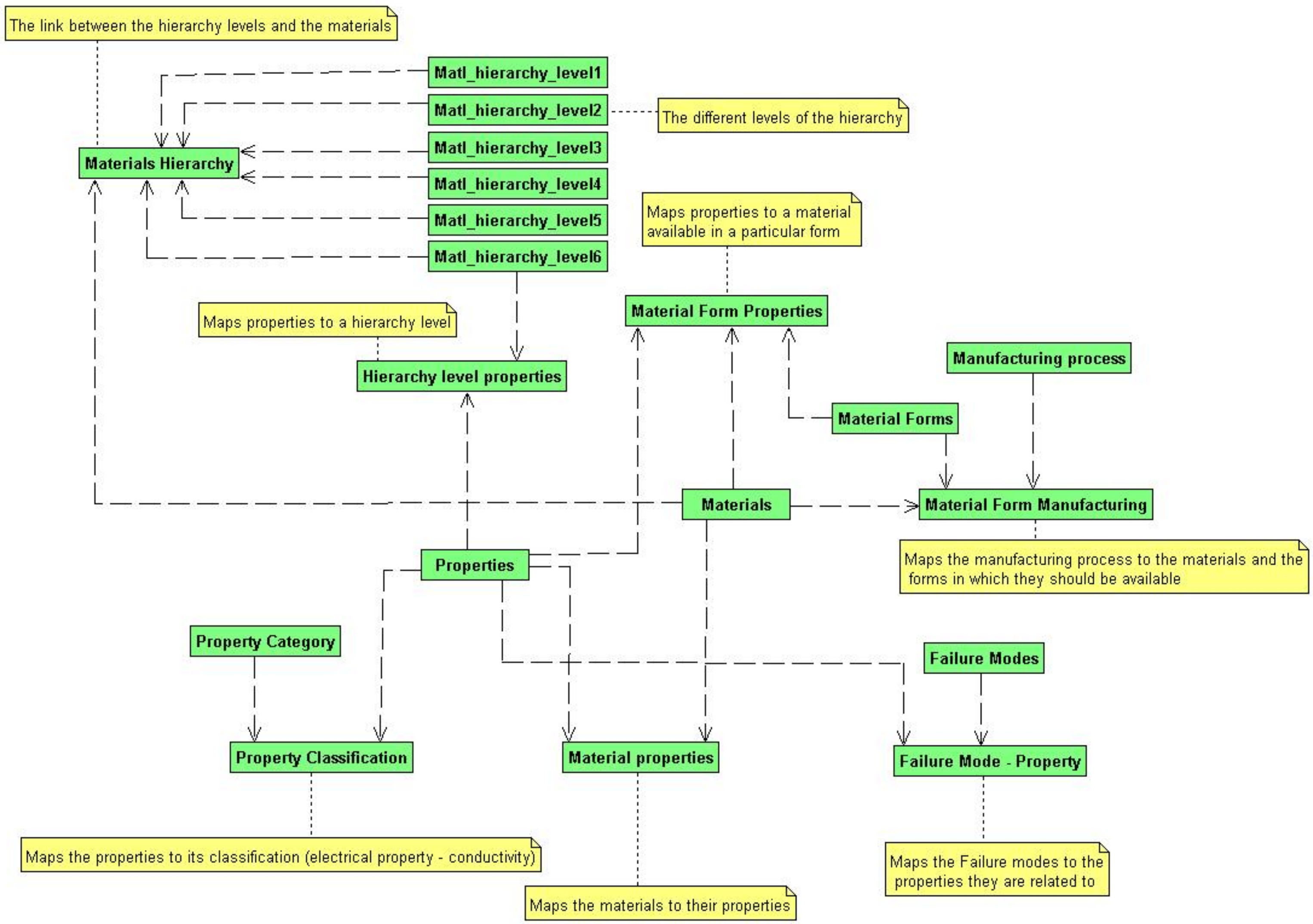
Step 4 is simply a table lookup; Given a failure mode, there are corresponding critical properties that are related to that failure mode.

Step 5 is based on the inputted information thus far, the bounds and material indices can be calculated using structural equations.

From there the candidate materials can be obtained.



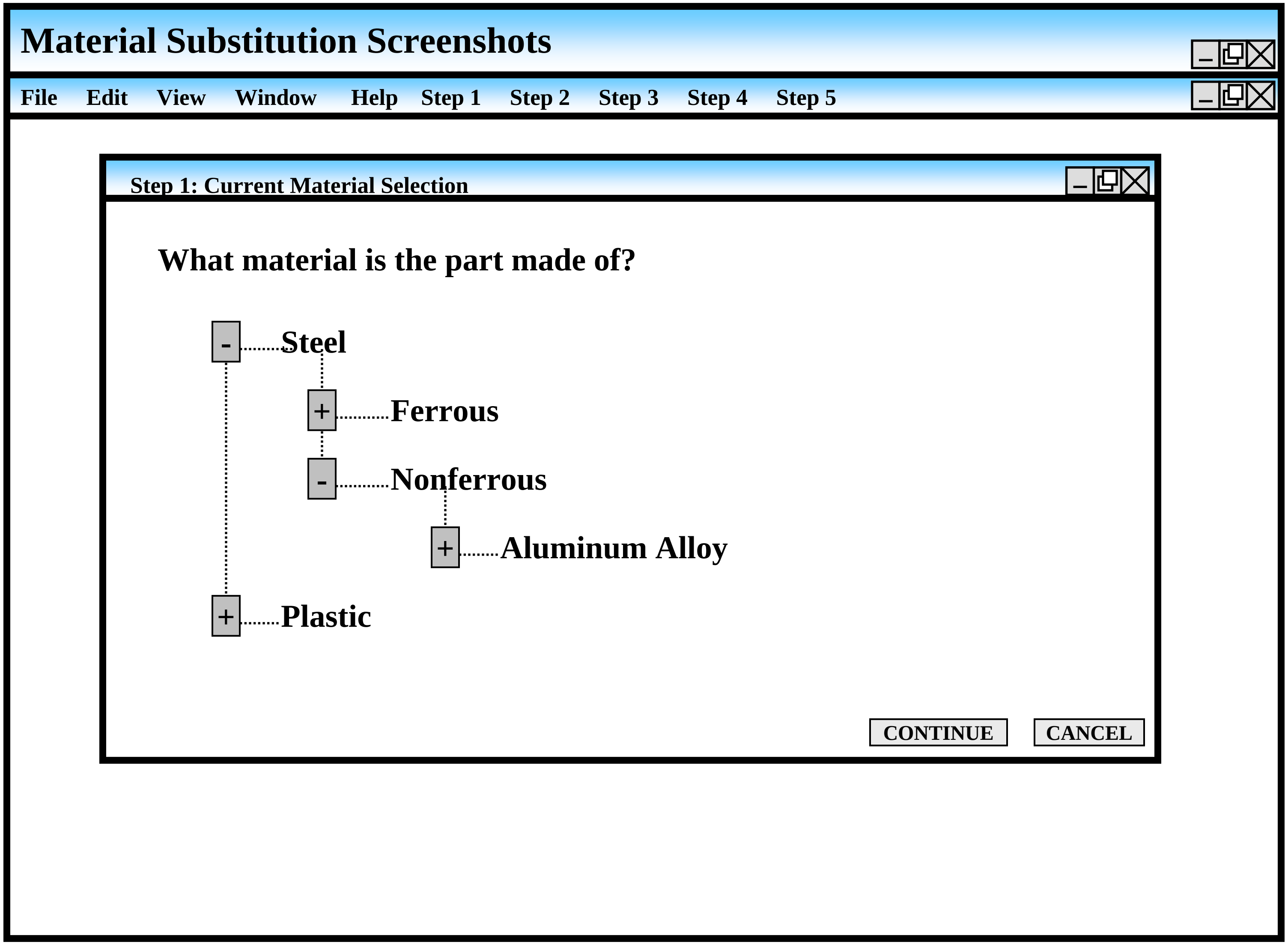
MatSub database contents



Material Substitution Rules

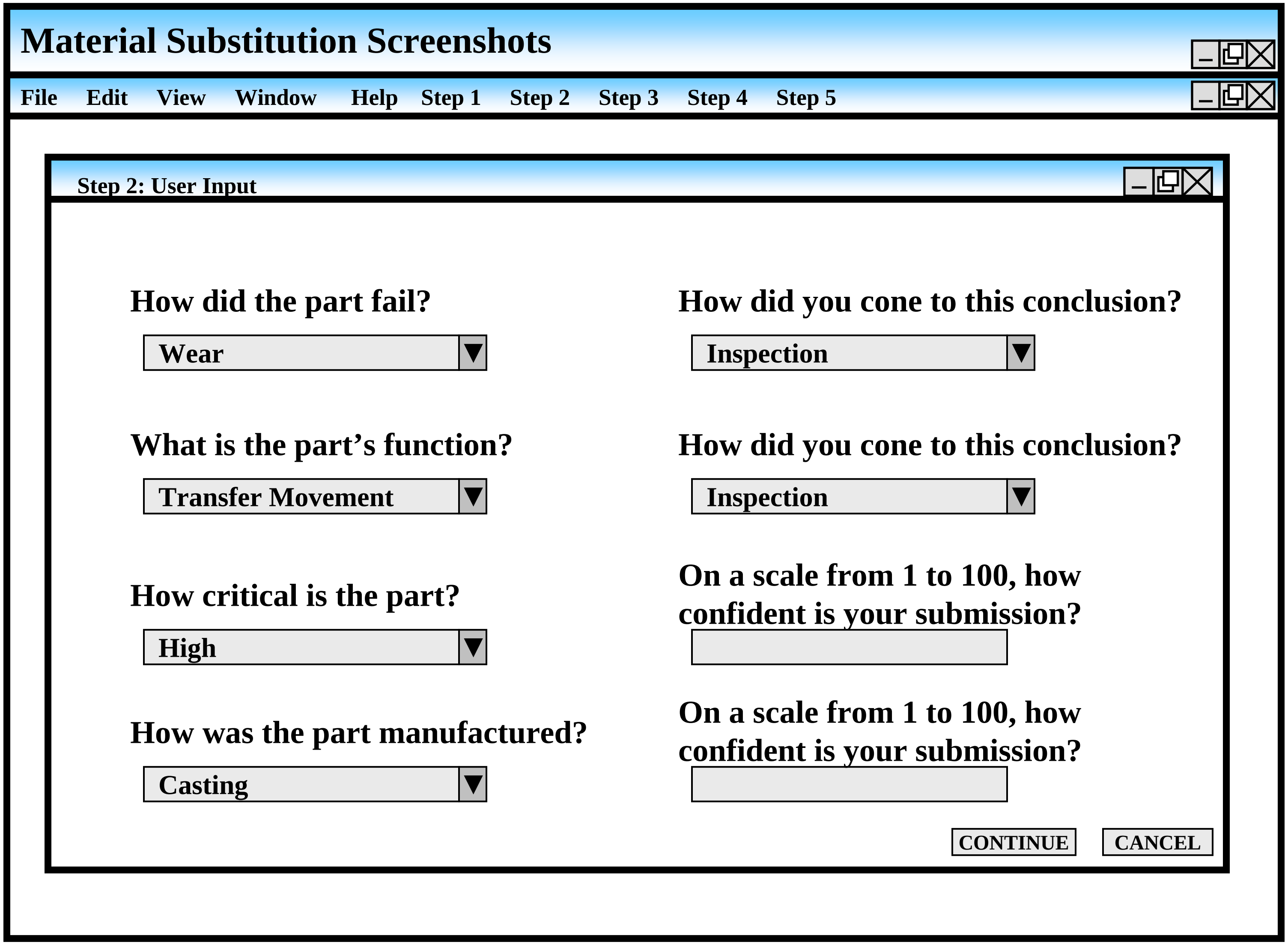
- **Step Five: Detailed Analysis and Selection**
  - Some drawbacks exist with using Ashby charts.
    - Property ratios cannot be determine for combined loads and/or combined stress.
    - Only 2 properties, or at most 3, are considered at a time.
  - Because of these limitations, a similar technique, with some adjustments, will be used.

Material Substitution Architecture



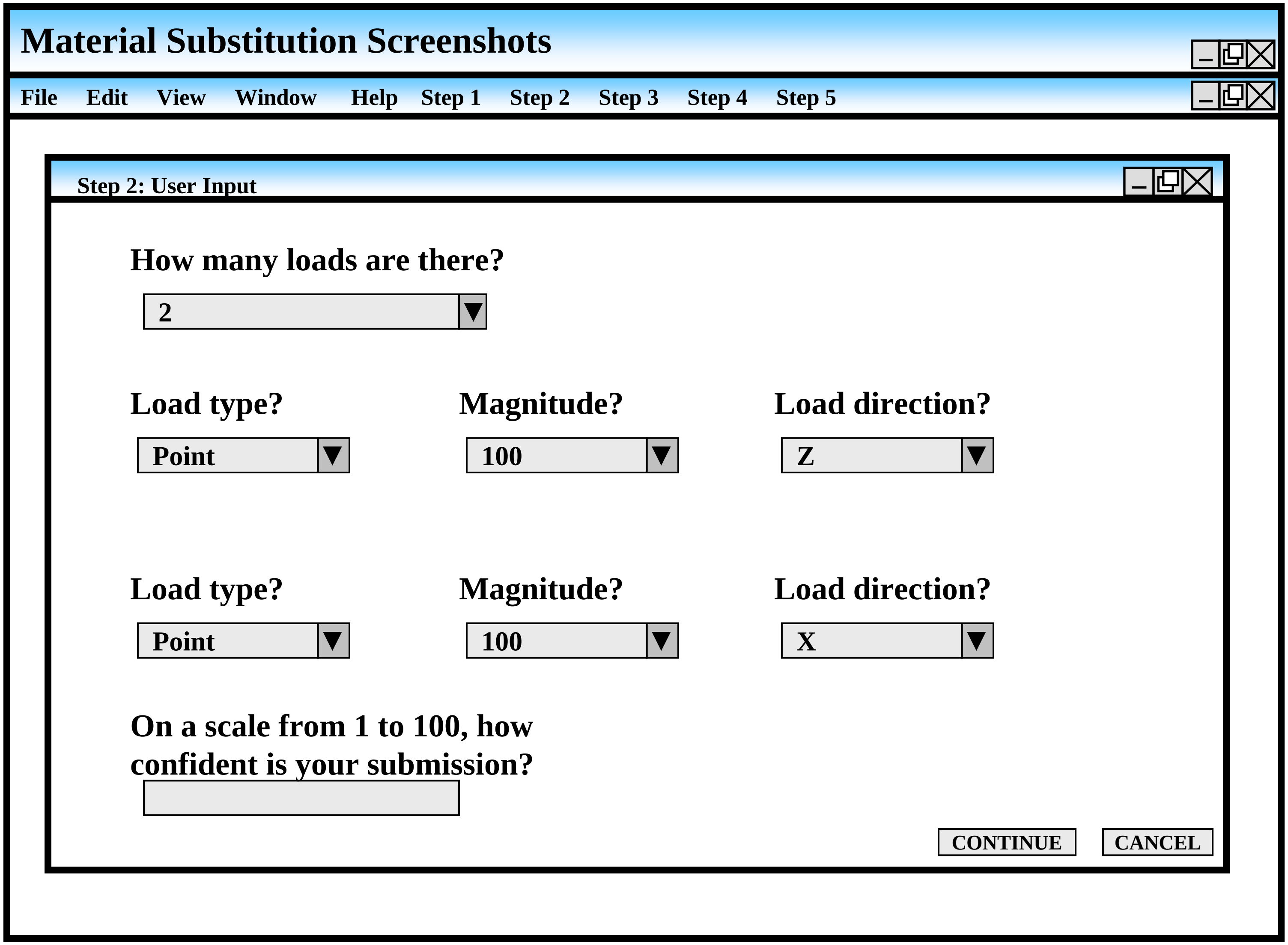
Initially the user chooses from steel or plastic. Then the user is able to narrow down the field to the next level of material type. Where the user stops, that is where either a specific material is chosen, if the user knows exactly what material it is, or average values are used.

Material Substitution Architecture



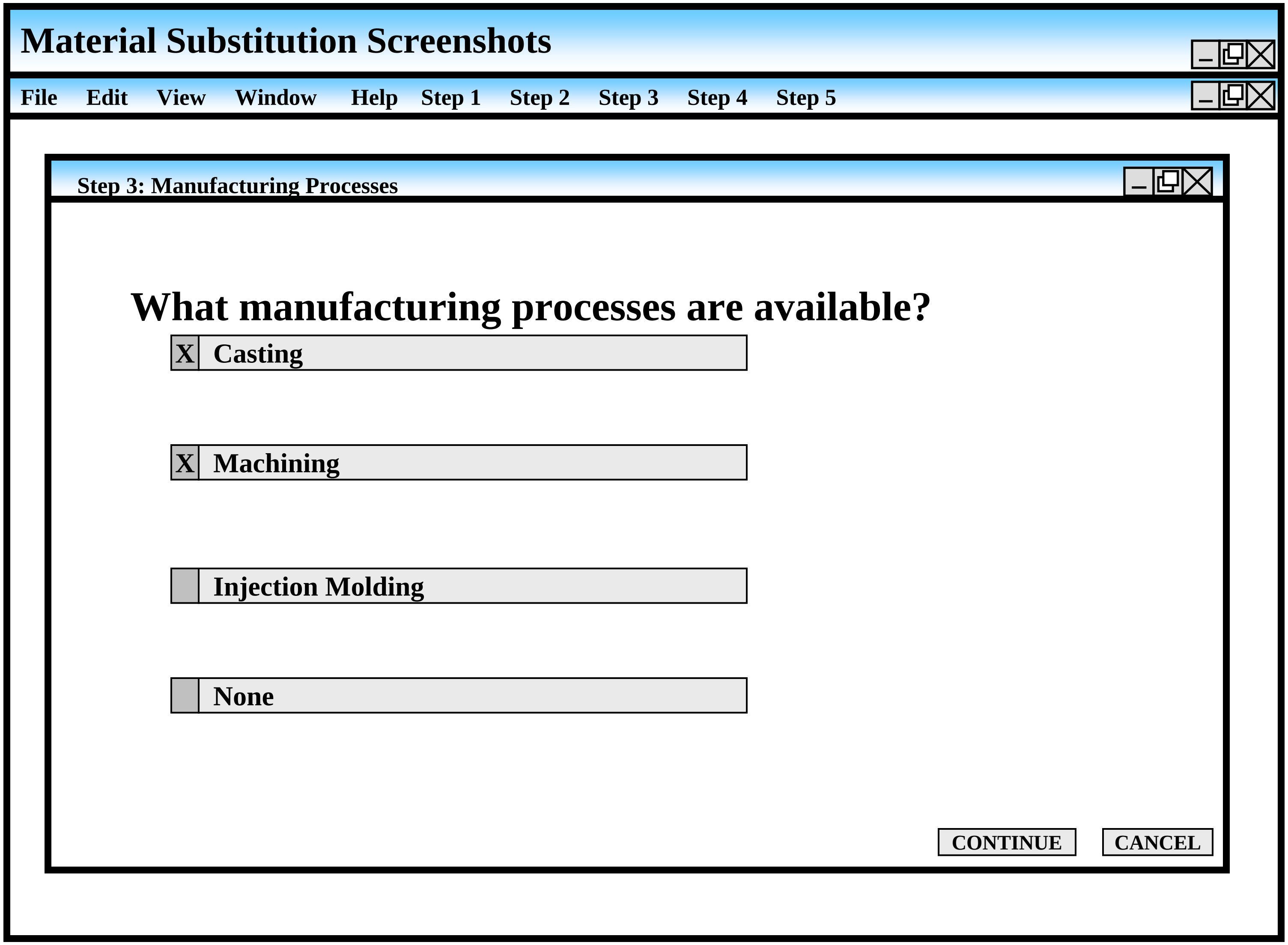
A series of questions are asked to the user (not all questions are shown). Some circumstances may need the user to enter a confidence level and others it may be better to find out how the user came up with the answer.

Material Substitution Architecture



User enters number of loads. Corresponding number of load entries are populated. Will need to find a way so that the load direction is standard on all of the parts.
After this step, critical properties are assigned based on user input.

Material Substitution Architecture



After this step, material property values are obtained.

Material Substitution Architecture

Material Substitution Screenshots

File Edit View Window Help Step 1 Step 2 Step 3 Step 4 Step 5

Step 4: Summary

Summary	
Current Part	
Material	Aluminum Alloy
Part Failure	Wear
Part Function	Transfer Movement
Part Criticality	High
Manufactured	Casting
Loads	Point, 100, Z
	Point, 100, X
Redesigned Part	
Available Manufacturing	Casting
	Machining
Available Materials	Bar Stock
	Plate Stock

OBTAIN MATERIAL SUBSTITUTION CANCEL

A Summary of input information.

Material Substitution Architecture

Material Substitution Screenshots

File Edit View Window Help Step 1 Step 2 Step 3 Step 4 Step 5

Step 5: Material Substitution

Too many materials to choose from. Please help narrow down the possibilities. Pick the material types to include in the search.

- [X] Ferrous
- [X] Nonferrous
- [ ] Thermoset Plastics
- [ ] Thermoplastic

OBTAIN MATERIAL SUBSTITIUTION | CANCEL

If there are too many materials to choose from, based on user's input, user is required to help narrow down the choices based on family of materials.

Material Substitution Architecture

Material Substitution Screenshots

File Edit View Window Help Step 1 Step 2 Step 3 Step 4 Step 5

Step 5: Material Substitution

No suitable material substitution was found. Please select next desired step.

- **Start Over** — Clears input information.
- **Change Some Input Information** — Does not clear input information and allows user to go back and change input.
- **Try Additional Questions** — Not sure what questions at this point. But maybe some additional questions may help narrow down choices.
- **Exit** — Exit program.

OBTAIN MATERIAL SUBSTITIUTION | CANCEL

Or if the program is unable to find a suitable material based on user input, the user is needed to either repeat the process, change some of the input information, or be asked additional questions. Starting over would be the least desirable.

Material Substitution Architecture

Material Substitution Screenshots

File Edit View Window Help Step 1 Step 2 Step 3 Step 4 Step 5

Step 5: Material Substitution

	Material	Critical Property 1	Value	Critical Property 2	Value
	Current Material				
	Aluminum Alloy	Yield Strength	245 Mpa	Modulus of Elasticity	73.2 Gpa
	Substitute Materials				
X	Aluminum Casting	Yield Strength	181 Mpa	Modulus of Elasticity	72.1 Gpa
	Aluminum Sand Cast	Yield Strength	215 Mpa	Modulus of Elasticity	71.0 Gpa
	Steel 1040	Yield Strength	290 Mpa	Modulus of Elasticity	200 Gpa
	Steel 1020	Yield Strength	350 Mpa	Modulus of Elasticity	205 GPA

EXPORT DATA CANCEL

After any iterations are completed and some or a material is narrowed down, the user is able to see some of the criteria by which a substitution is made. The user is able to choose which material to substitute.

Design Automation Laboratory

Material Substitution Architecture

Material Substitution Screenshots

File Edit View Window Help Step 1 Step 2 Step 3 Step 4 Step 5

Final Review

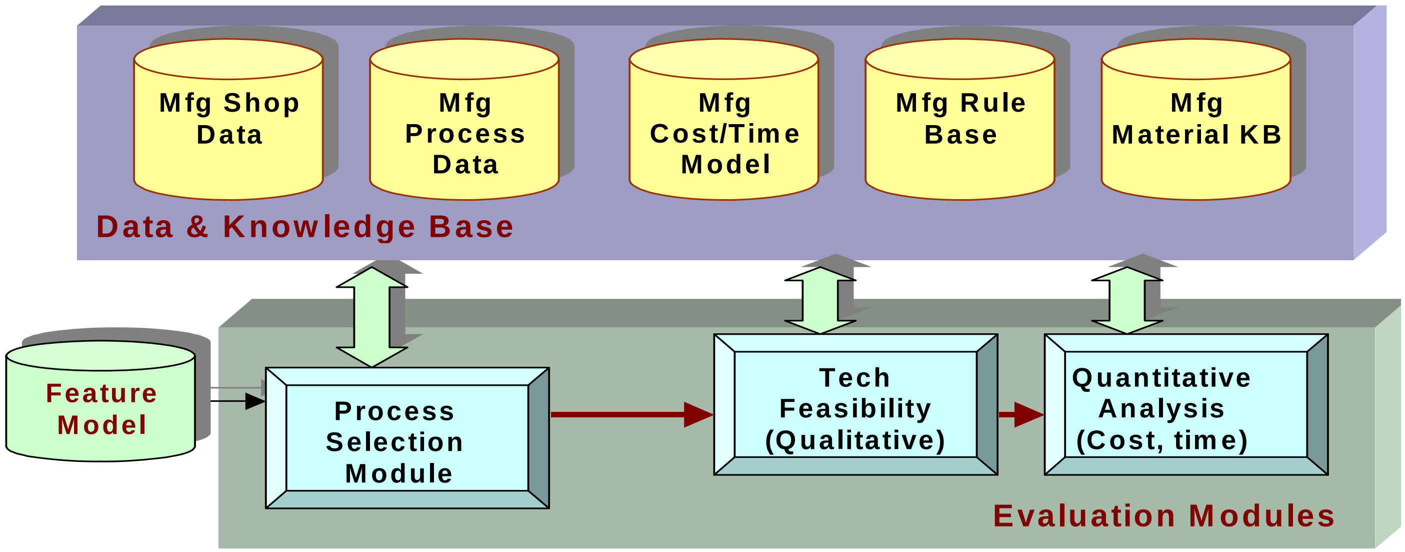
Summary			
Current Part			
Material	Aluminum Alloy		
Part Failure	Wear		
Part Function	Transfer Movement		
Part Criticality	High		
Manufactured	Casting		
Loads	Point, 100, Z		
	Point, 100, X		
Redesigned Part			
Available Manufacturing	Casting		
	Machining		
Available Materials	Bar Stock		
	Plate Stock		
Chosen Material			
Aluminum Casting	Yield Strength	181 Mpa	
	Modulus of Elasticity	72.1 Gpa	
	Ultimate Tensile Strengt	365 Mpa	
	Shear Strength	290 Mpa	
	Poisons Ratio	0.33	

SAVE EXIT

When export data button is pressed, a summary screen appears with information for printing. User is also allowed to save info to desired location as a text file.

Customizable DfM module

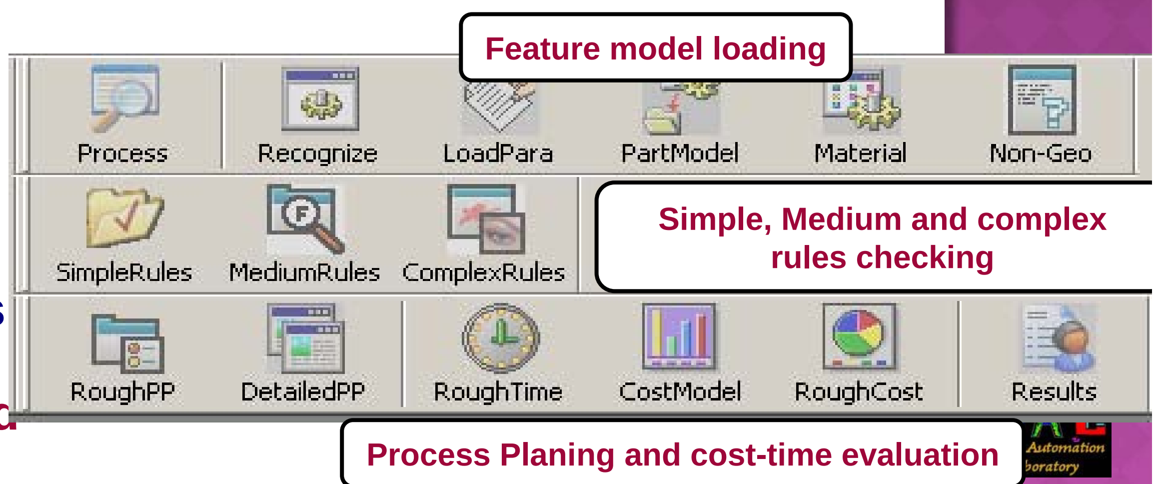
- **DFM Advisor, previously developed in the DAL, offers a robust and customizable framework for manufacturability analysis.**



•The DFM Advisor is linked to several databases :

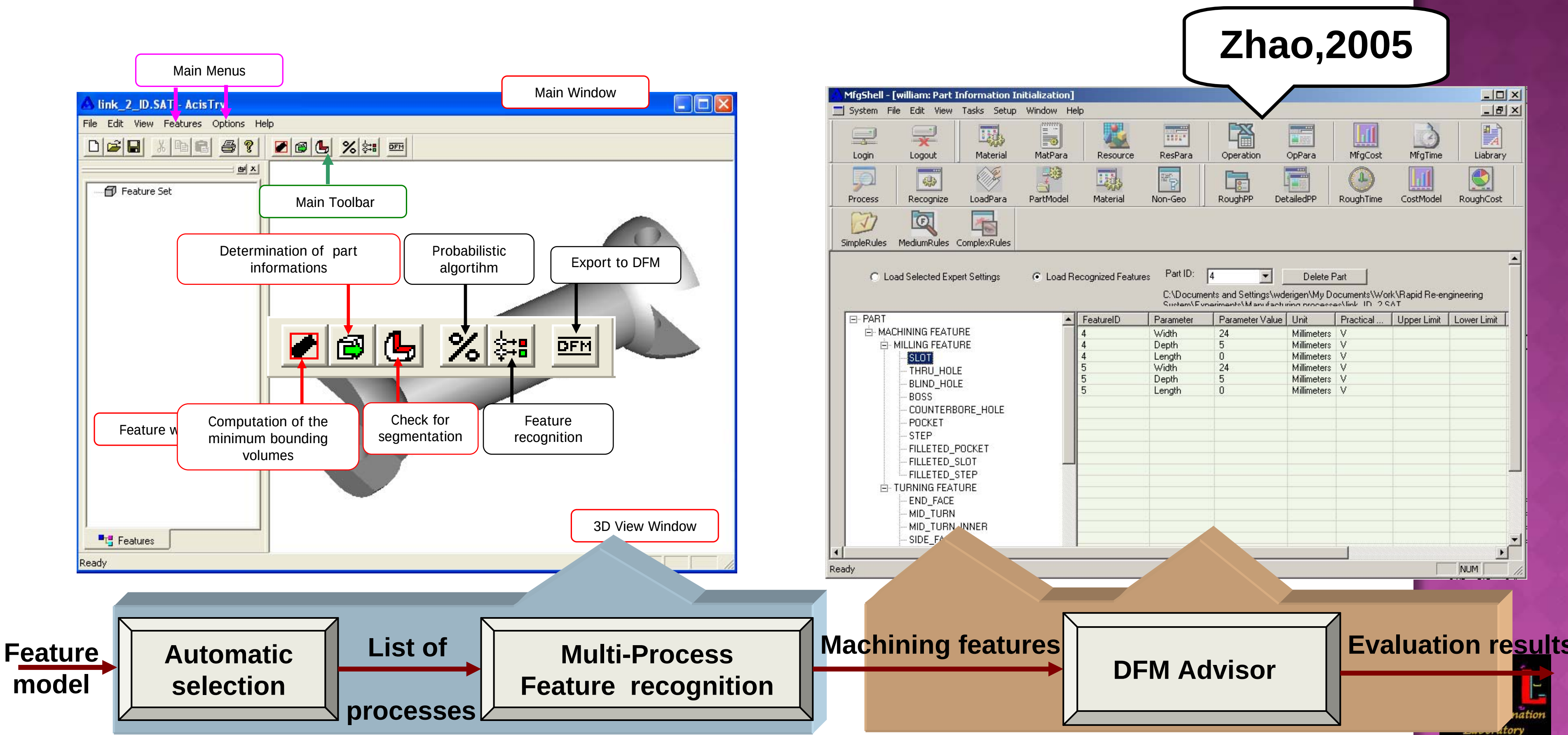
- **–Resources,**
- **–Rules,**
- **–Features,**
- **–Manufacturing processes**
- **–….**

•Each of these databases could be customized by an expert



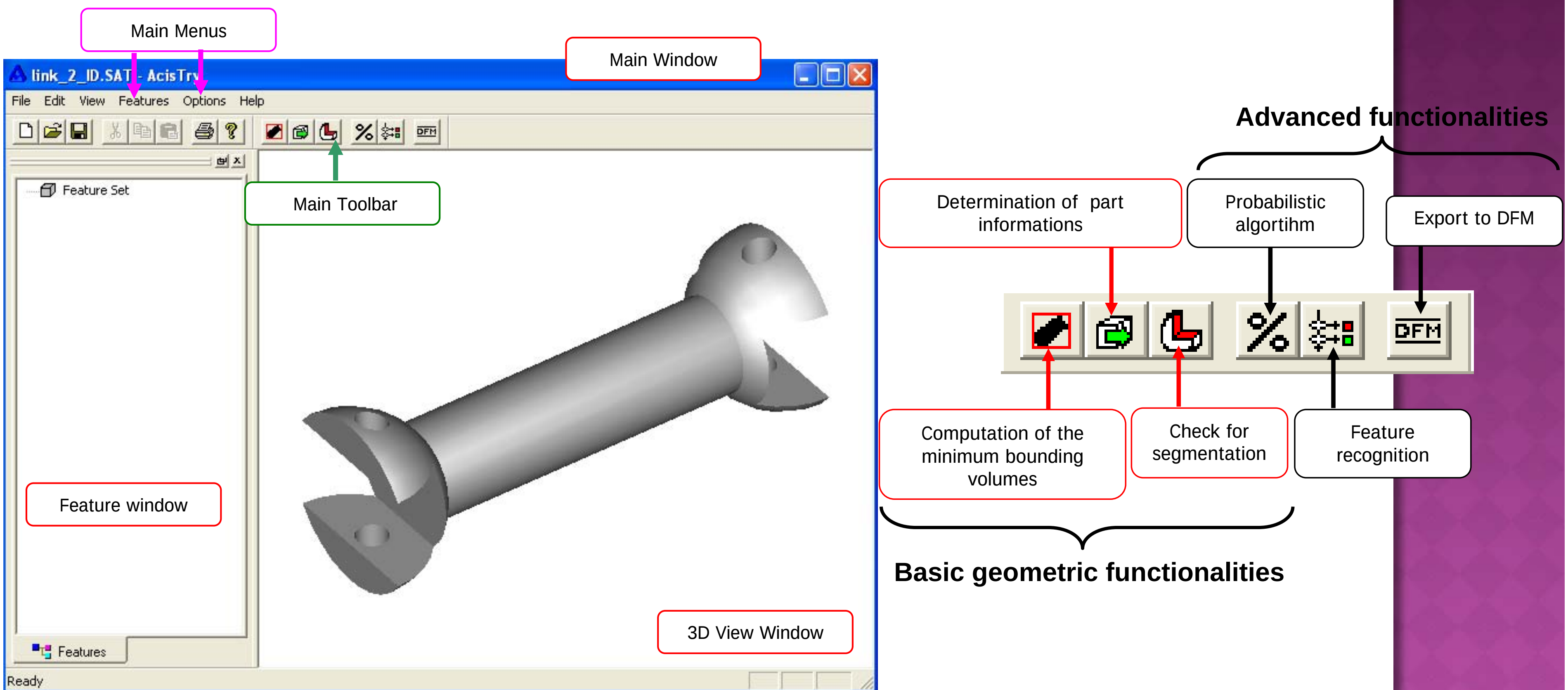
New developments

- **An application has been coupled with the DFM Advisor for analyzing geometric characteristics of a part, classifying it (turned, milled, mill-turn, sheet metal), making a preliminary process selection, selecting the appropriate set of feature recognizers, and exporting the features and parameters to DfM.**

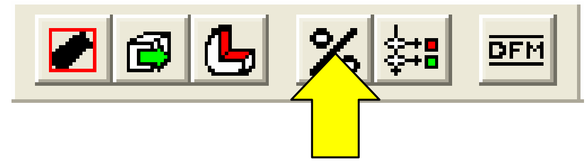


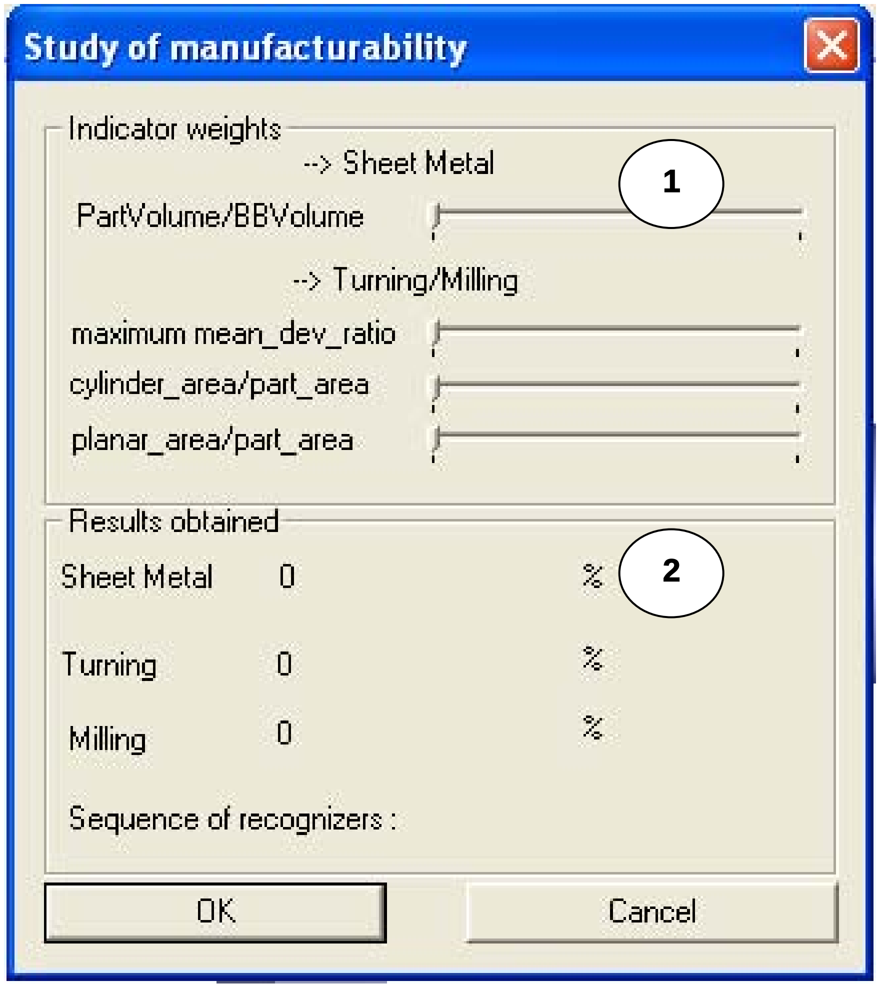
DfM Demo System

- **Main interface. The following will describe the advanced functionalities**



"Probabilistic" Process selection

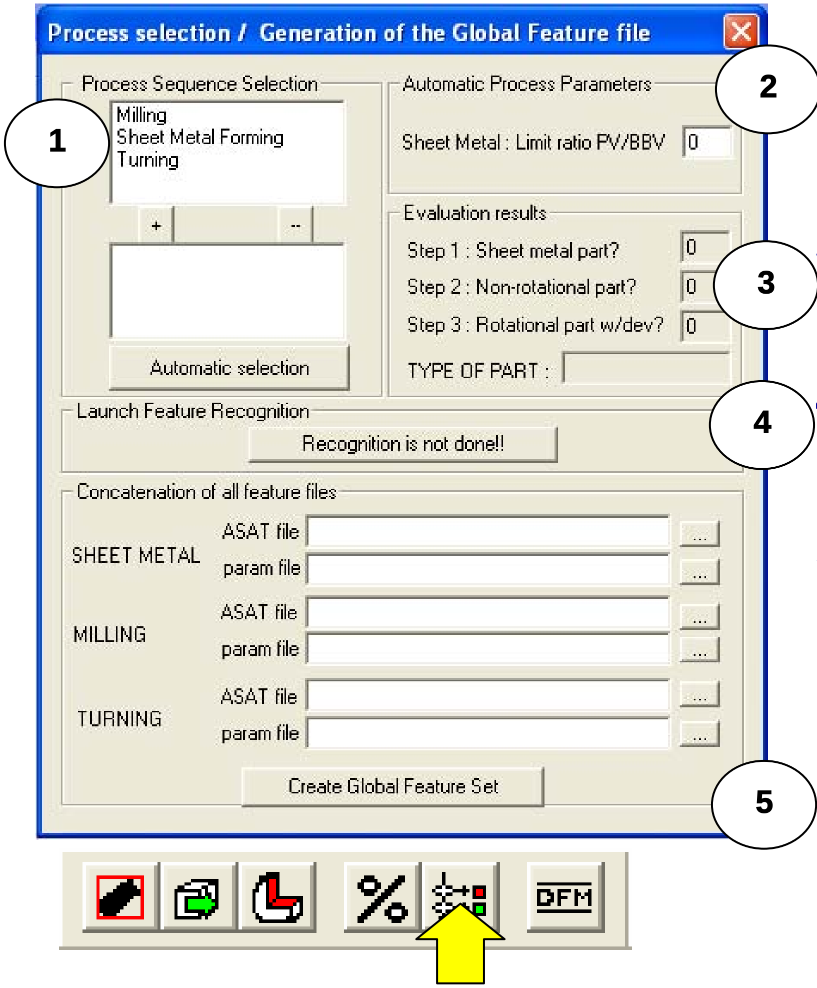




1 – Indicator weights: the weights of each indicator taken into account into the evaluation process. The sliders provide a simple way to experiment and fine tune the value of the weights

2 – Resuts obtained: the probability that the part can be manufactured by this process/ the percentage of the part features manufacturable by a process

Preliminary process selection and feature generation



1 – Process sequence selection: the available processes to be selected (manual or automatic). The order of the selected processes determines their priority

2 – Automatic process parameters: the parameters needed for automatic selection

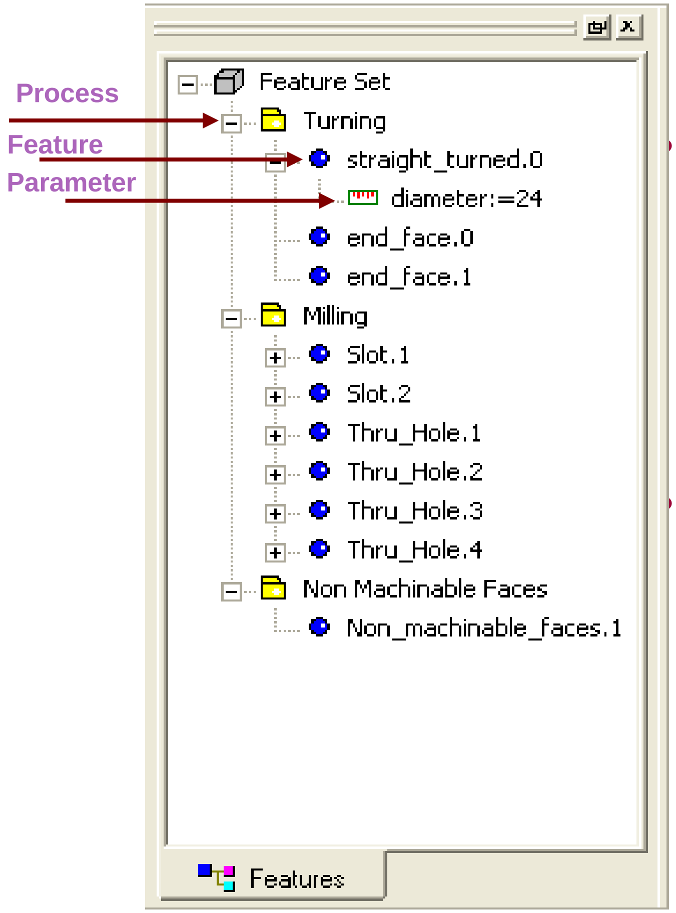
3 – Evaluation results: the results of the evaluation steps and the type of the part

4 – Launch feature recognition: launches each needed feature recognizer in order

5 – Concatenation of all feature files: After the recognition phase, each selected process has its ASAT and PARAM file. The conjugation of these two files provides all the information about the recognized features related to this process. The file paths are entered into this form to create the global feature set.

Feature viewing & editing

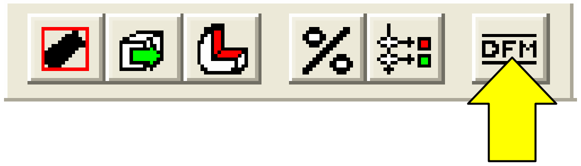
- Interface for



- **Classification of features:** a tree structure organized in a way that each feature belongs to a generic manufacturing process; the feature parameters represented as leaves of the tree.
- **Editing of the feature parameters:** due to some complex topological situation, a recognizer may not be able to determine one parameter value. To overcome this limitation, a modification dialog is available.
- **Detection of non-machinable faces:** once the global feature set is created, some of the faces of the geometric model could be not associated with any feature. This event could result from:
  - A manufacturability problem (the process can not do this face),
  - A feature definition problem (one UDF is not well defined or is missing).

Exporting Manufacturing Features

- **Interface for the export of the feature set to the DFM Advisor**
  - This command converts the feature set into a text file.

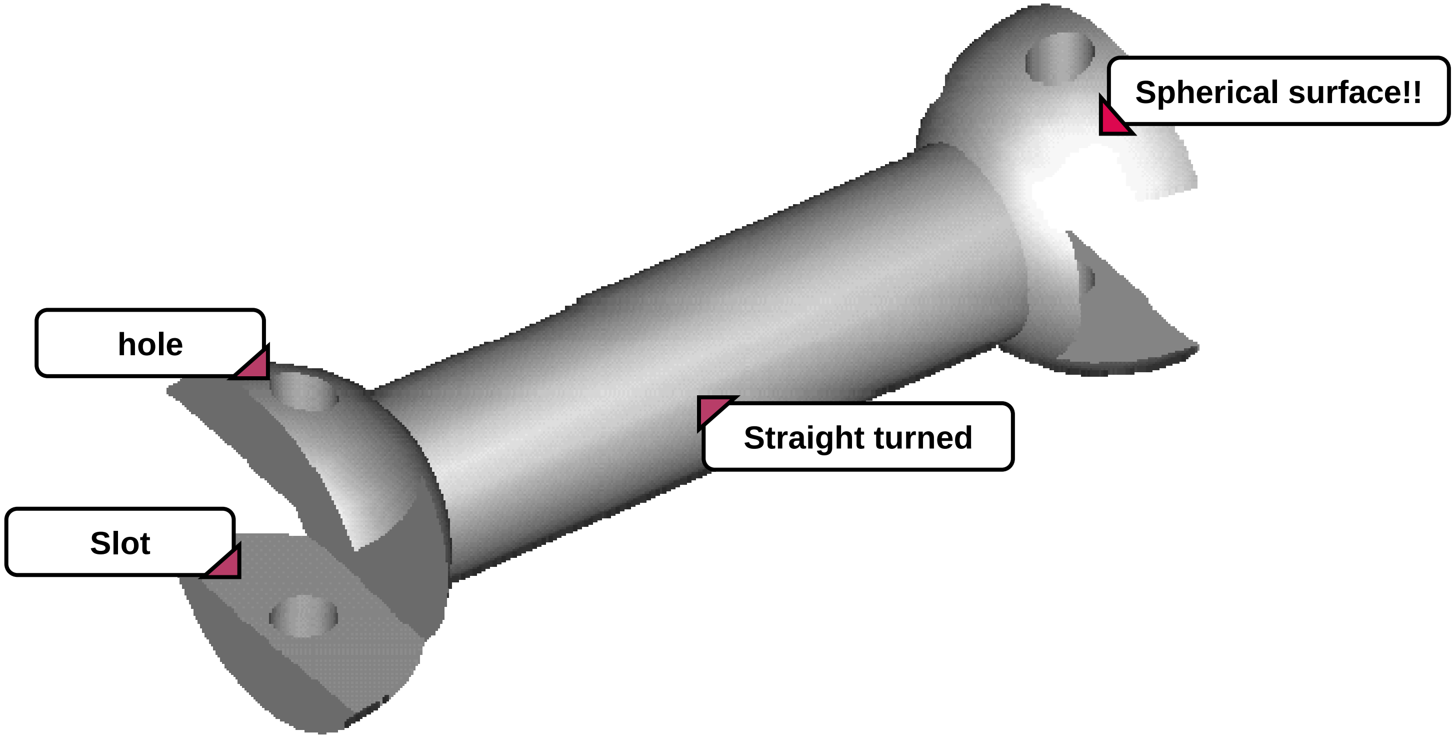


- **The user has to enter his name and a part identification number, which will be used by the DFM Advisor to store the feature set.**

- **The generated text file is totally compatible with the DFM Advisor.**

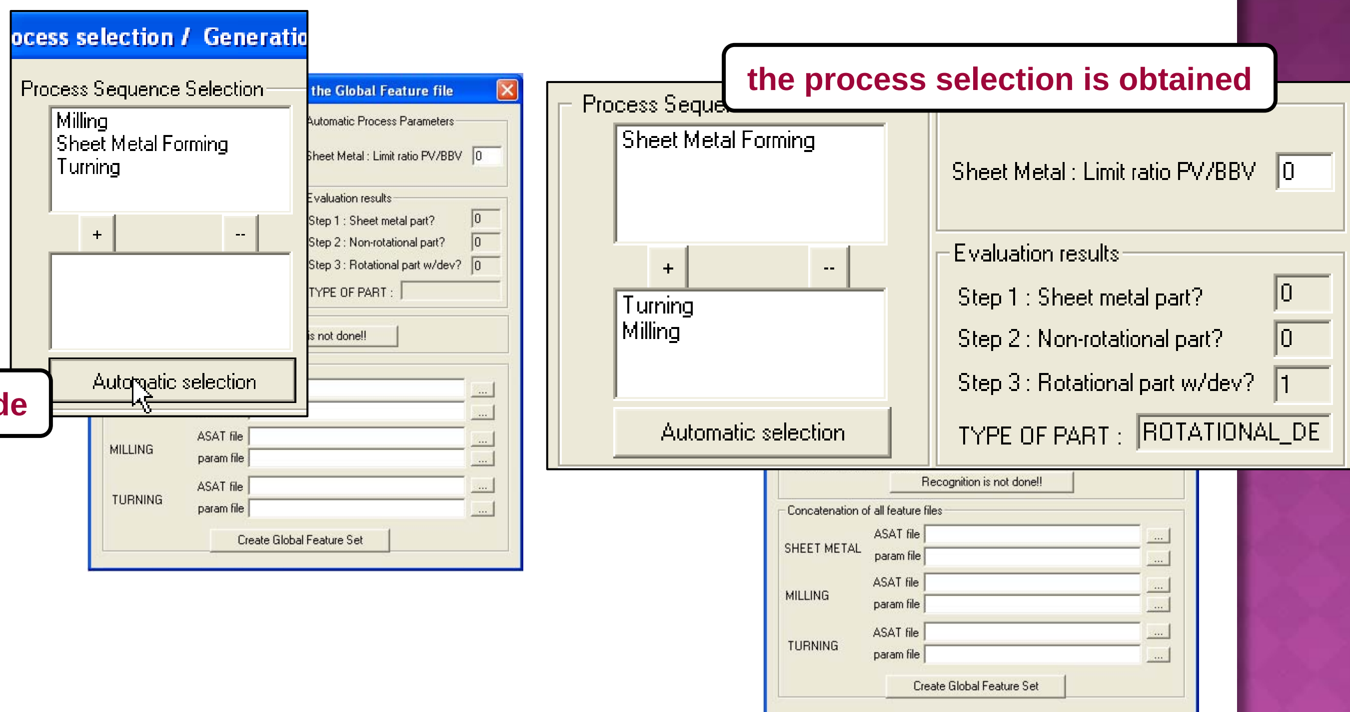
Case Study

- **Example of the feature generation process on a simple part : a link between two joints.**
  - Milling and turning features are present on the part,
  - The spherical surfaces are non manufacturable with available processes.



Case Study

- **Step 1: Automatic Process selection**

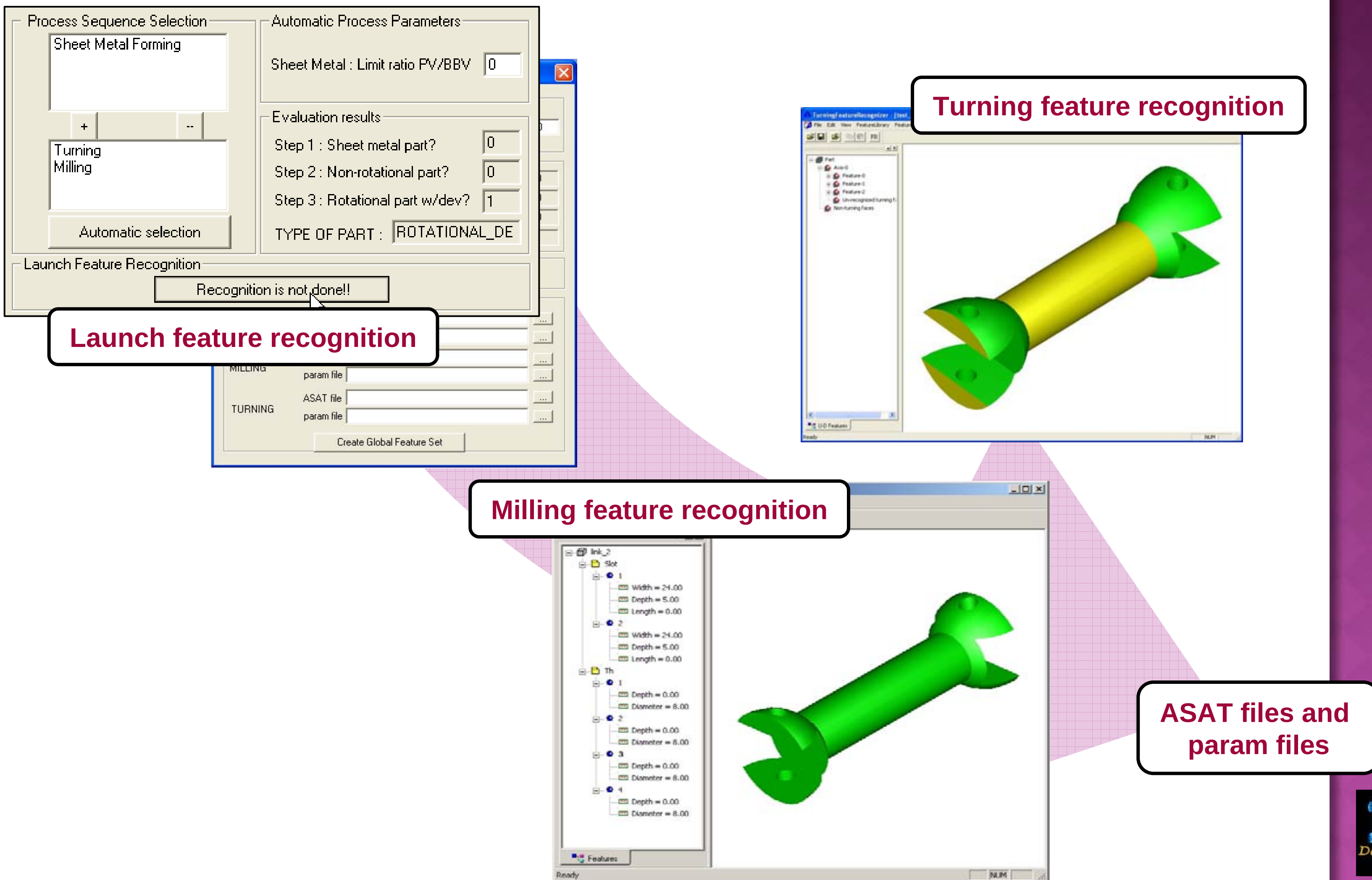


the process selection is obtained

Selection of Automatic mode

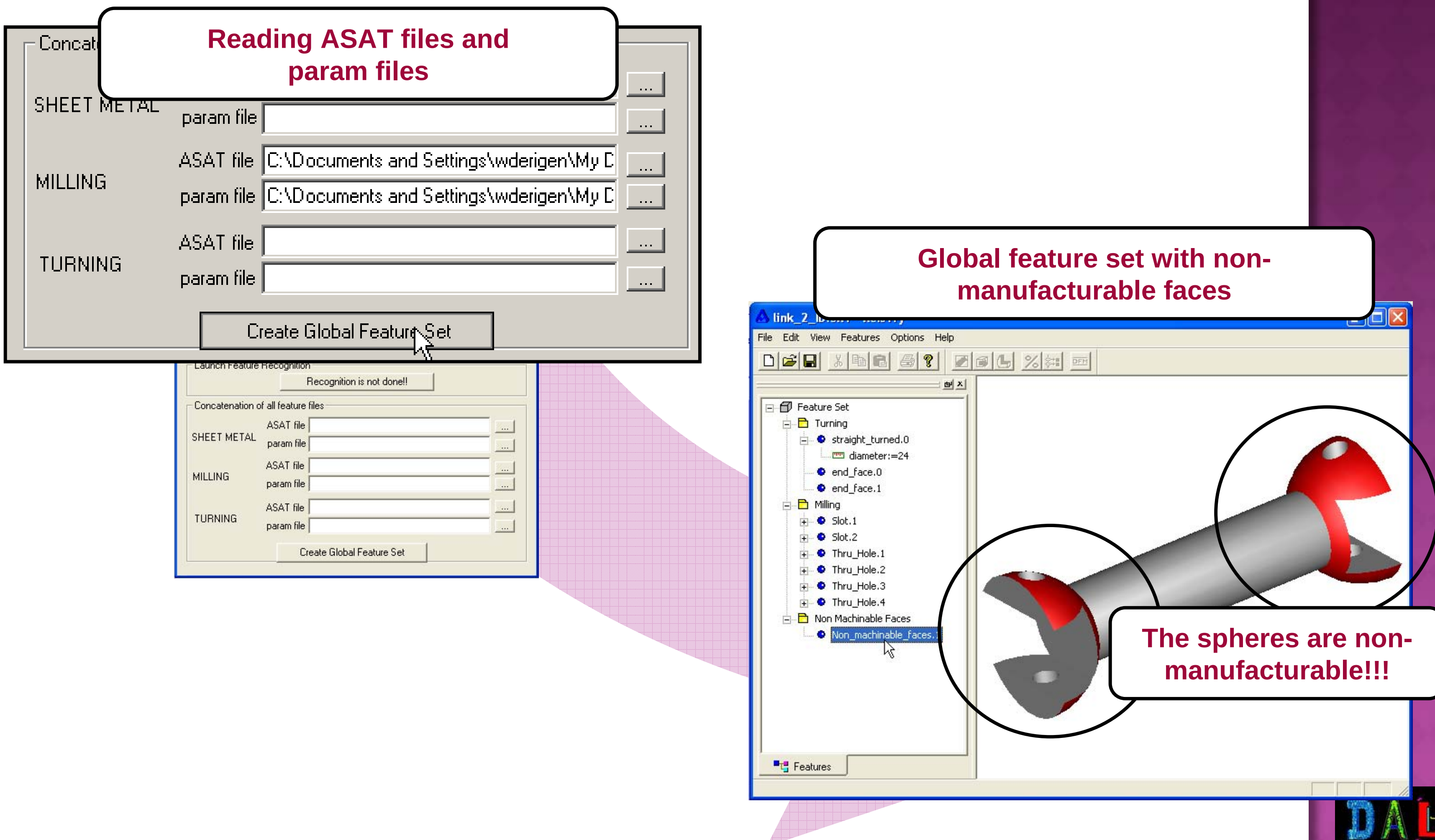
Case Study

- Step 2: Feature recognition



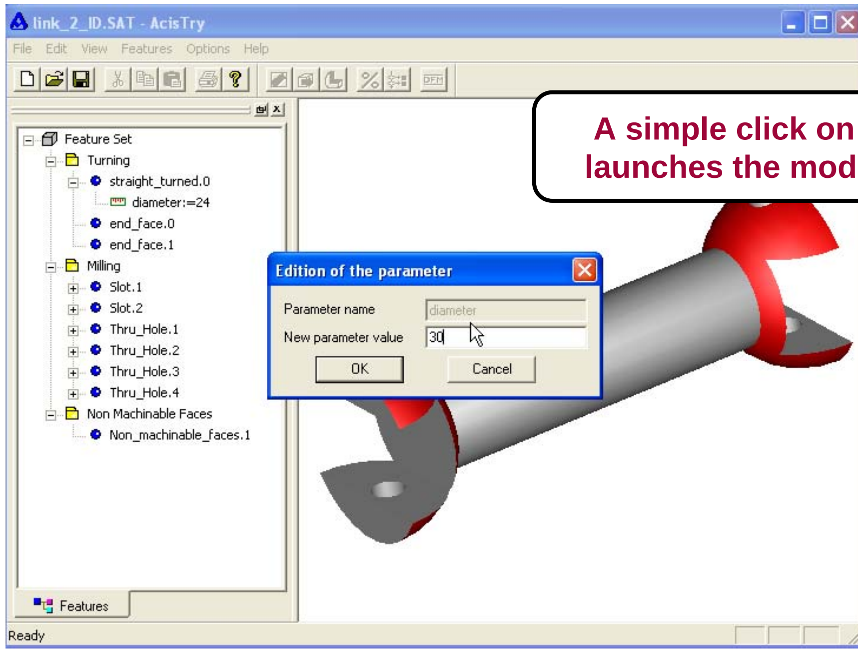
Case Study

- Step 3: Generation of the global feature set



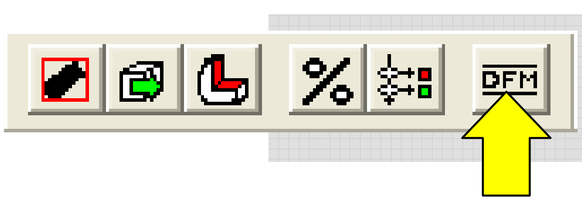
Case Study

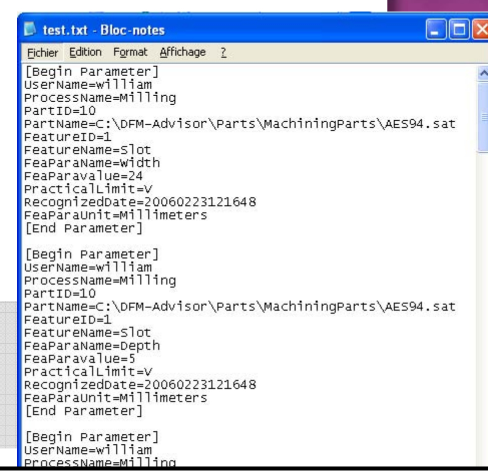
Step 4: Modification of feature parameter



A simple click on the parameter launches the modification dialog

Step 5: export to DFM Advisor

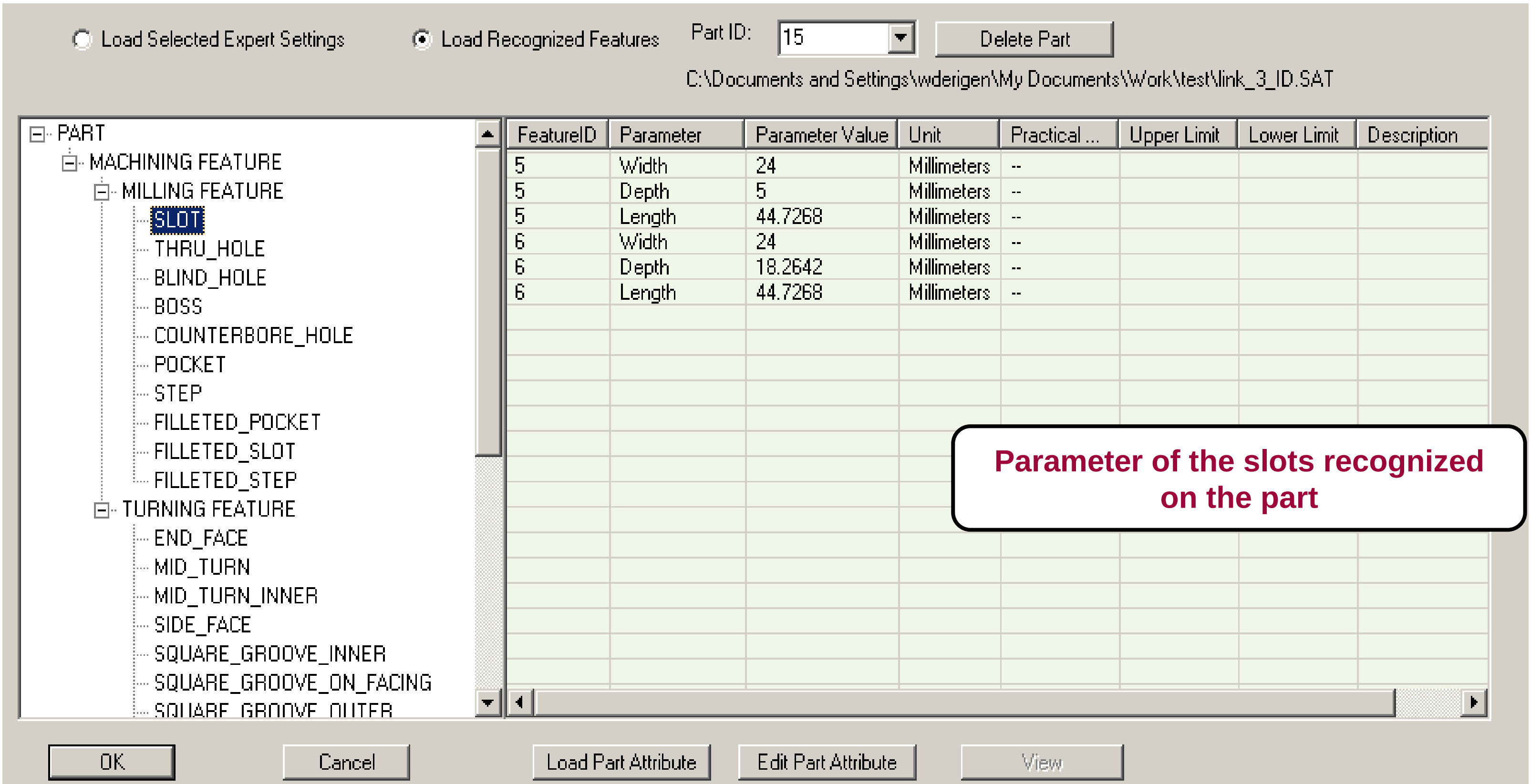




The textfile for the DFM Advisor

Case Study

- Step 6: Open the file with the DFM Advisor



- Step 7 (to come): manufacturability study and re-design